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Space Sports – Sailing in Space

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Abstract: Titan is the largest moon of Saturn, and apart from the Earth it is the only body in our solar system where a liquid exists on the surface. Within the last ten years a system of lakes and rivers have been discovered. The climate and seasonal cycles of Titan are still not very well known, but the composition and pressure are fairly well established. Perhaps in the future boats will sail the lakes of Titan for research purposes or even sport. The purpose of this paper is to give an overview of the concept of space sports, the conditions of Titan and to calculate important parameters of sailing such as floatability, stability, hull resistance and sail forces. This paper shows that if a sailing yacht on Titan will have twice as large displacement as on Earth, it will be 2.6 times less stable for the same beam. Since friction will be smaller, it will be faster than on Earth at low speed, but significantly slower at high speeds due to the wave generation. The same sail area is required to get the same sail forces if the average wind is 3 m/s, while a 9 times larger sail area is required for if the wind speed is only 1 m/s.

1 INTRODUCTION

Today the International Space Station has been manned since the year 2000. Serious plans of sending humans to Mars in the near future exist. The European Space Agency is discussing having a manned base on the Moon by 2030. Perhaps humanity one day will colonize a large part of our solar system. The idea of sports then being practiced in space is probably not too strange. Space Sports would be performed under very different conditions than Earth Sports, and completely new possibilities would arise.

Sports research indicate new records being harder and harder to obtain in some sports. Possibly, the limits of human capability for certain sports will soon be reached. But, one could argue, only on this planet! On other planets it might be possible to jump higher and patterns of locomotion and the motion of objects will differ. Earth Sports could be adapted and new sports could be created. Could interplanetary championships exist? Could an athlete from Earth compete against an athlete from Mars? How, and on which planet in that case?

There are a large number of sports that could be investigated using physics and technology. How high could a horse jump on Mars? Can you sail on the lakes of Titan, the largest moon of Saturn? How large would a goal in soccer have to be on the moon? Can you fly using muscular power on Pluto? What is the pattern of locomotion when running in a different gravity? Is The Jovian moon Europa the perfect place for skating? How do you play ball in zero gravity? Can you ski on Olympus Mons, the highest mountain in the solar system?

The number of possible questions about space sports are almost endless. This paper introduces one concept study of space sports by looking at sailing on Titan.

2 A BRIEF OVERVIEW OF OUR SOLAR SYSTEM

Our sun is a medium sized yellow star, one of the approximately 200 billion stars in the Milky Way galaxy. Around the sun there are eight planets and minor bodies such as dwarf planets, moons, asteroids and comets.

The planets are usually divided into two separate categories; terrestrial planets and gas giants. The terrestrial planets are Mercury, Venus, Earth and Mars in order from the sun and outwards. The gas

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giants are Jupiter, Saturn, Uranus and Neptune. Terrestrial planets are substantially smaller than the gas giants with the diameter of Jupiter being 22 times larger than the diameter of the Earth. Rocks and metals are the main constituents of the terrestrial planets, while the gas giants have large layers of hydrogen, helium, ices and hydrocarbons in different states surrounding rocky cores.

The distance between the Earth and the sun is some 150 million km, and this distance is usually referred to as 1 Astronomical Unit (1AU). Mars is located at 1.5 AU, so the four terrestrial planets are fairly close together when it comes to astronomical distances. Jupiter is at 5.2 AU from the sun and the outmost planet Neptune is at 30 AU.

Most of the bodies of the solar system orbit the sun in the same plane, the only exception being the large spherical cloud of comets surrounding the sun.at the outskirts of our solar system.

3 LIQUIDS ON PLANETARY AND LUNAR SURFACES

Oceanus Procellarum – Sea of Storms, Mare Crisium – Sea of Crises, Mare Tranquillitatis – Sea of Tranquillity and Mare Imbrium – Sea of Rains

The names of the dark areas on the moon are most likely exciting for any sailor. Indeed, their names reflect a time when they were mistaken for being oceans and seas instead of the dry lava plains we now know them to be. No liquid water can exist on the surface of the moon primarily due to the absence of an atmosphere.

Large amounts of liquids on the surface of a planet or a moon is in fact extremely rare in our solar system. Titan, the largest moon of Saturn, is probably the only place excepting our own Earth. The seas, lakes and rivers of Titan are however not filled with water but the hydrocarbons methane and ethane in liquid state.

Since Titan then is the only other body in our solar system with a liquid on the surface, it is also the only other place where we could practice sailing. Will we ever do that, and why in that case?

Most likely the first expeditions to Titan would be for scientific purposes much like the way we are exploring Mars today. The exploration of Mars is partly being done using robotic rovers, and on Titan robotic boats could be an option. A great advantage of sailing is it being a form of transport without the need of extra energy sources. In space exploration, energy is always one of the limiting and costly factors.

The research on autonomous vehicles on the Earth is evolving rapidly, and autonomous boats on Titan would be an enormous advantage since the communication time between the earth and Titan is an approximate hour. NASA is currently discussing the possibility of sending a submarine to Titan.

Of course, the possibility exists of Titan being colonized in the future. Manned sailing boats could then become reality and apart from transport perhaps even sailing could become a recreational pleasure as well as a sport.

Why then are the Earth and Titan the only bodies in our solar system with liquids on their surfaces? The uniqueness of Titan is the conditions being right for the existence of a relatively thick atmosphere. A certain atmospheric pressure is necessary for the existence of liquids instead of having a substance in solid or gaseous state. The surface pressure on Titan is larger than on the Earth, and the atmosphere of Titan consisting mainly of nitrogen.

Our neighbor planet Mars has such a thin atmosphere that liquid water can hardly exist on the surface anymore. Large amounts of water are present on Mars, but almost all the water is in solid state (ice) with the transition to water vapour being very quick when heated. The lack of atmosphere on Mars is due to a weak gravity and no shielding magnetic field. The solar wind is a stream of electrons and protons from the sun, and it exerts a pressure on the Martian atmosphere. On Earth our atmosphere is partly shielded by our magnetic field. The weak Martian gravity has not been able to hold on to the originally much thicker atmosphere when battered by the solar wind.

Jupiter and Saturn are our two largest planets and they are called gas giants. Both have more than 60 moons each. Several of these moons are exciting worlds in different sizes and with varied surfaces. A few of the moons are actually larger than the planet Mercury. A planet moves around the sun, and a moon moves around a planet but planets and moons can be of equal sizes. Titan is the second largest moon in our solar system, but it is smaller than Mars in both radii and mass. Why then has Titan not lost its atmosphere when Mars has? The reason is it being much colder out by Saturn at 9.5 AU than at Mars at 1.5 AU. The average temperature on Titan is around -180 degrees. This will lead to the velocities of the molecules in the atmosphere not being as high. It is easier for the gravity to hold on to a cooler gas than a hot one, since fewer of the molecules reach the escape velocity. Titan is also shielded from the solar wind by the magnetic field of Saturn.

Already in the 1980’s the speculations of lakes on

Titan began triggered by data from the Voyager space crafts. When the Cassini space craft arrived after a ten year long journey in 2004 hopes were high of a rapid detection of the lakes. But it took three more years until the lakes were finally proved to exist in 2007. Today we know that the largest lake of Titan Kraken Mare has a surface of 400 000 square kilometers and a depth of 160 m. Its surface is probably just a little bit smaller than the surface area of Sweden and possibly larger than the Caspian Sea. Titan has several other lakes and rivers of different sizes and depths and shows an intriguing landscape. Measurements so far indicate flat lakes and low velocities of the winds, but modelling of Titans climate shows possibilities of strong winds and even hurricanes. This has received support by other studies of the landscape.

Saturn orbits the sun with a period of approximately 29 years. The seasons are therefore some 7 years each. When Cassini reached Saturn in 2004 the northern hemisphere of Titan was in deep winter. Now, twelve years later the northern hemisphere is approaching the summer solstice. This means that we have not as yet had the opportunity to study the climate of Titan during a whole "Titan-year". Therefore it is quite uncertain how valid the weather observations are when it comes to average conditions.

4 THE POSSIBILITY OF SAILING ON TITAN

So, what are the possibilities of sailing on Titan, and how different would it be from sailing on Earth? Would it be at all possible, and what would the boats look like? To assess the possibilities we need to consider aspects like floatability, stability, hull resistance and sail forces. These properties are in turn dependent on physical constants like the density and viscosity of the atmosphere and the liquid, and on the gravity. Wind speed is of course also an important parameter. In Table 1 the physical constants are listed, based on data from Cassini. For comparison, the corresponding values on the Earth are also presented.

Table 1: Physical constants (Hayes et al, 2013).

Constant	Titan	Earth
Atm. density, ρ_a [kg/m^3]	5	1.2
Atm. viscosity, ν_a [m^2/s]	1.3x10^{-6}	15x10^{-6}
Liquid density, ρ_l [kg/m^3]	530-660	1030
Liquid viscosity, ν_l [m^2/s]	0.3x10^{-6}-3x10^{-6}	10^{-6}
Acc. of gravity, g [m/s^2]	1.4	9.8

Let us start with the floatation, i.e. how deeply the boat will float in the liquid. The gravity force F_G (downwards) is obtained as

$$F_G = mg \tag{1}$$

where m is the total mass of the boat and g is the acceleration of gravity. The buoyancy force, F_B (upwards) is equal to

$$F_B = \rho_l D g \tag{2}$$

Where ρ_l is the liquid density and D is the submerged volume (*displacement*) of the hull. This is according to Archimedes' principle. At equilibrium

$$F_G = F_B \tag{3}$$

which yields

$$D = m/\rho_l \tag{4}$$

Since g appears both in F_G and F_B it disappears from the final equation, which says that for a given mass the displacement is inversely proportional to the fluid density. According to Table 1 the density on Titan is about half of that on Earth. Therefore the displacement will be twice as large on Titan as on Earth for a given mass.

Stability is of fundamental importance for a sailing yacht. As appears from Figure 1, it is achieved through the sideward movement to leeward of the centre of the underwater volume from B to B' when the yacht heels (Larsson et al, 2014). Since F_B acts at the centre of buoyancy, it will create a righting moment with F_G. A vertical line along F_B will cut the heeled center plane of the yacht at the metacenter, M. The distance between this point and the centre of gravity G is called metacentric height and is denoted $\overline{GM}$. It follows that the righting arm, RM, can be computed as $\overline{GM}\sin\phi$, where ϕ is the heel angle, and that the righting moment, RM, is

$$RM = F_G \overline{GM} \sin\phi \tag{5}$$

To compute the righting moment we need the metacentric height $\overline{GM}$. This can be computed using the distance from B to M, $\overline{BM}$, which is obtained from a fundamental formula in stability theory (Larsson et al, 2014)

$$\overline{BM} = I/D \tag{6}$$

where I is the moment of inertia around a longitudinal axis of the area inside the waterline of the hull.

For a sailing yacht, B and G are close together and $\overline{BM}$ and $\overline{GM}$ are approximately equal. With this approximation, and using (1) for the gravity, the righting moment is

$$RM = mg \sin\phi \, I/D \tag{7}$$

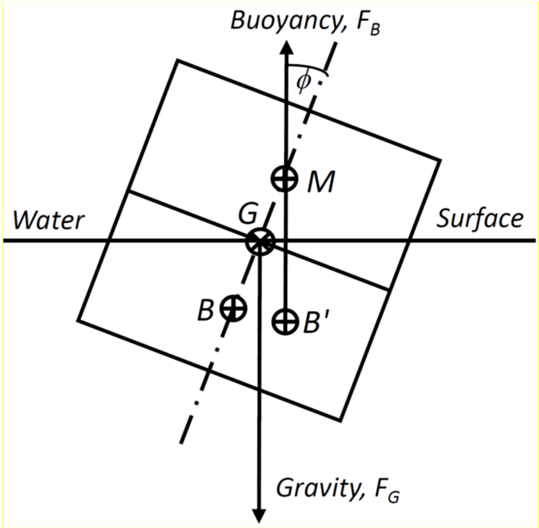

Figure 1: Stability principle.

For a given mass and heel angle the righting moment is thus proportional to g and I/D. As seen in Table 1, the gravity on Titan is seven times smaller than that on Earth, so for the same stability I/D has to be 7 times larger. Now, for a given length, the inertia I is proportional to beam cubed, while the displacement D is proportional to beam to the first power. It the follows that I/D is proportional to beam to the second power. For I/D to be 7 times larger than on Earth beam has to be increased $\sqrt{7}$ times, i.e. about 2.6 times.

A hull with the same length as on Earth, but twice as beamy would satisfy the displacement criterion above but it would be less stable. To remedy this, the hull could be longer and it could carry more ballast. The main parameter of interest may be the payload the yacht can carry. For a given displacement this depends on the weight of the yacht itself. The heavier the yacht, the smaller the payload. The weight increases with beam, but much more so with length. So from this point of view it is better to make the hull wider. This will however increase resistance, as we will see. Another very interesting possibility is to use a catamaran. Then stability is no problem and the resistance low.

Having considered the most important properties, floatability and stability, we now turn to the speed potential of the yacht. This is determined by the driving forces on the sails and the resistance of the submerged part of the yacht. Let us start with the latter.

There are two main components of resistance for a body moving along the surface of a liquid: friction and wave resistance. The former occurs because of the internal friction in the fluid, its viscosity, while the latter is caused by the generation of waves transmitted from the body.

Similarity laws for scaling resistance (Larsson and Raven, 2010) show that friction, R_F, may be computed as

$$R_F = C_F 0.5 \rho U^2 S \tag{8}$$

where C_F is a friction coefficient, ρ the fluid density U the fluid velocity and S the wetted surface of the body. C_F is determined by the Reynolds number, R_n

$$R_n = UL/\nu \tag{9}$$

where L is a characteristic length of the body and ν the kinematic viscosity of the fluid.

Table 1 gives a range of possible viscosities for the liquid on Titan. The range is however centered around the value on Earth (10^{-6} m^2/s). Since the dependence of C_F on R_n is essentially logarithmic (Larsson and Raven, 2010) it is enough for the present discussion to note that the order of magnitude is the same for the liquid viscosity on Titan and Earth. We can thus assume the same C_F. For a given speed, friction is then proportional to ρS. As we have seen the density on Titan is half of that on Earth, but the wetted surface is larger if the hull is made twice as wide. However, not so much that it compensates for the lower density. Friction may thus be assumed somewhat smaller on Titan.

As shown in Larsson and Raven (2010) the wave resistance is governed by the Froude number, F_n.

$$F_n = U/\sqrt{gL} \tag{10}$$

Neglecting some higher order effects, a constant Froude number will imply the same wave pattern (scaled with length) and the same wave resistance coefficient, C_W, regardless of the speed, length and gravity. The wave resistance, R_W, is obtained from the coefficient in the same way as the friction in equation (8)

$$R_W = C_W 0.5 \rho U^2 S \tag{11}$$

Unlike C_F, C_W will not be the same as on Earth. This is for two reasons. A wider hull will give a larger C_W, and, more importantly, a given speed will give a higher Froude number on Titan, thereby increasing C_W. The first effect can be roughly estimated as proportional to beam, i.e. for double beam a twofold increase for a given Froude number. But the second effect is difficult to estimate. The relation between C_W and F_n. is very nonlinear, and also dependent on the hull shape. For most standard yachts there is a maximum Froude number around 0.45, where the wave resistance gets so large that the driving force from the sails is insufficient for increasing the speed. This limit will now occur at $\sqrt{7}$ times smaller speed than on Earth, due to the 7 times smaller gravity (see Equation 10). In fact the whole wave resistance/speed curve will be compressed in the speed direction by a factor $\sqrt{7}$.

At low speeds friction dominates over wave resistance and, as seen above, the speed may then be somewhat larger on Titan, but at higher speeds the total resistance depends mainly on the wave resistance, and then the speed will be considerably smaller due to the Froude number effect.

Finally, let us look at the sail forces. The sail is a wing which generates a force with components in the direction of motion, F_x and at right angles to that, F_y. Both can be obtained in a similar way as R_F and R_W

$$F_x = C_x 0.5 \rho_a V^2 S_s \quad (12)$$

$$F_y = C_y 0.5 \rho_a V^2 S_s \quad (13)$$

where C_x and C_y are coefficients ρ_a the density of the atmosphere, V the wind speed and S_a the sail area. Like for the liquid, the coefficients depend on the Reynolds number

$$R_{na} = VC/\nu_a \quad (14)$$

where C is the mean chord of the sail and ν_a is the kinematic viscosity of the atmosphere.

The wind speed on Titan is not well known. There are indications of occasional hurricanes, but the normal wind speed should be quite low. According to Habib (2015) the average speed is estimated to about 3 m/s. Other sources quote lower speeds, around 1 m/s (Hayes et al., 2013, Bird et al 2005). On Earth the average wind speed is 6.6 m/s (Habib, 2015).

Let us first assume a wind speed of 3 m/s. As seen in Table 1, the atmospheric viscosity on Titan is about 1/10 of the viscosity on Earth, so the Reynolds number according to equation (14) is about five times larger for a given sail. This yields a slightly lower friction coefficient on the sails, but this will have a very small effect on the forces, which are almost exclusively caused by pressure differences between the two sides of the sail. We can thus assume that both C_x and C_y are the same on Titan and Earth for a given sail. Equations (12) and (13) then show that the forces are proportional to ρV^2. Table 1 shows that the atmospheric density on Titan is about four times that on Earth, but on the other hand, the wind speed is only about half in our assumption. So ρV^2 turns out to be the same! The sail forces will thus be unchanged.

The other scenario with an average wind speed of 1 m/s will yield 9 times smaller forces! To get the same sail forces on Titan as on Earth the sail area has to increase 9 times!

A factor speaking in favour of the lower wind speed is that no waves have been observed on the lakes of Titan. This may however be a matter of measurement accuracy (Hayes et al., 2013). If the wind speed is only 1 m/s very small waves will be generated and they will not influence performance. However, if the speed is 3 m/s the waves could be significantly larger than the average on Earth. This is due to the fact that the forcing of the waves, pressure variation in the atmosphere, is the same, as we have seen, but the gravity and density of the fluid lower. Such large waves will slow down a sailing yacht considerably, at least sailing upwind.

5 CONCLUSIONS

Titan is the largest moon of Saturn, and apart from the Earth it is the only body in our solar system where a liquid exists on the surface. Within the last ten years a system of lakes and rivers have been discovered. The climate and seasonal cycles of Titan are still not very well known, but the composition and pressure are fairly well established. Perhaps in the future boats will sail the lakes of Titan for research purposes or even sport. This paper addressed some of the issues that will have to be considered before sailing on Titan, or even designing a boat for sailing on Titans lakes. A sailing yacht on Titan will have twice as large displacement as on Earth, it will be 2.6 times less stable for the same beam. Since friction will be smaller, it will be faster than on Earth at low speed, but significantly slower at high speeds due to the wave generation. The same sail area is required to get the same sail forces if the average wind is 3 m/s, while a 9 times larger sail area is required for if the wind speed is only 1 m/s. To avoid the stability problem a catamaran seems to be a good choice!

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