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Physics of Planets
Group Project

Lightning on Titan

Overview

Atmospheric electricity has been studied for centuries. Lightning was discovered to be an electric phenomenon by Benjamin Franklin in the 1850s, and since then there has been much advancement in the theory of its generation. On Earth, microphysical processes such as cosmic-ray absorption and particle collisions lead to ionization in storm clouds. Rising convective currents in the clouds then lead to massive charge separation; electrons, with much smaller mass than the positive ions, are carried upwards much more efficiently than the ions. The base of the cloud becomes positively charged, and the middle region becomes negative (Interestingly, the topmost part of the cloud also becomes positive, likely due to positive ions trapped in very light ice crystals which are blown to the top). Eventually the electric field generated by this charge separation grows strong enough to ionize the air along a channel from the base to the middle of the cloud, creating a highly conductive pathway. Charge is then free to flow along this pathway, which is heated to thousands of degrees Kelvin by Joule heating. We call this incandescent flash lightning. (Desch, 2002)

Lightning events dump a huge amount of energy into atmospheric gases. This opens the door to many chemical reactions which could not otherwise occur. On Earth, much of the NO_x in the atmosphere is thought to be produced in this way. On Jupiter, C_2H_2 and HCN are similarly produced. Lightning has also been detected on Uranus and Saturn, though there is debate about whether Venus has lightning. The Cassini-Huygens probe was anticipated to detect electrical activity on Titan, the largest moon of Saturn. Spectroscopic readings of the atmosphere indicate about forty times more acetylene than predicted from equilibrium chemical reactions in the atmosphere, which is composed primarily of Nitrogen, about four percent methane, and a host of other minor constituents, such as organic compounds. Lightning in this environment is posited to be the source of this excess acetylene. However, as of yet there has been no positive detection. Cassini has made over thirty flybys of the moon while orbiting Saturn, and the Huygens probe actually penetrated the atmosphere and successfully landed on the surface - all without detecting any of the radio-frequency (RF) signals of electrical activity in the atmosphere (Desch, 2002).

Background

The search for lightning on Titan started after the Voyager 1 made a Titan flyby in 1980, which revealed Titan's thick atmosphere that is composed of ninety percent nitrogen (Wilson). Soon after, much theoretical and experimental research has been carried out to study the complex atmosphere and lightning condition on Titan, and the results were very promising. Studies have shown that Titan is able to possess thunderclouds through moist convection, which accumulate free charges in the atmosphere to produce a huge electric field up to $2 * 10^6\ V * m^{-1}$, enough to generate a cloud-to-ground type 2 lightning similar to the one on Earth (Tokano et al. 2001). Although the recent mission to Titan, the Cassini-Huygens mission, was not yet able to detect a positive lightning signal during the 72 Titan flybys, the Cassini was able to confirm the existence of three main cloud regions on Titan – the North pole, the South pole, and the southern midlatitudes of about 40 degree (Fischer & Gurnett, 2011).

Following the Voyager 1 mission, the Cassini-Huygens mission has carried out a more extensive study and search for lightning on Titan. Cassini was equipped with the onboard Imaging Science Subsystem (ISS) and the Radio and Plasma Wave Science (RPWS) instruments that are capable of detecting lightning whistlers and high frequency (HF) radio signals at two different HF bands, HF1 (325-1800 kHz) and HF2 (1.8-16 MHz) (Fischer et al. 2007). Most radio signals have to be above a certain cut-off frequency to penetrate the ionosphere and reach the HF receiver. Thus the HF1 is effective for detecting radio signals above the cut-off frequency, and the HF2 is effective for detecting signals above the frequency range in which interference from Saturn is dominant. Huygens landed on Titan in 2005, and was equipped with the Huygens Atmosphere Structure Instruments (HASI) that is able to measure the electrical properties of the atmosphere.

With 72 Titan flybys, the Cassini has not yet been able to detect a solid signal of lightning on Titan. Data collected by the RPWS need to be carefully analyzed to distinguish lightning radio signals from spacecraft interferences or solar radio emissions. The RPWS data during the T61 flyby displayed radio bursts that were unfortunately caused by Saturn's lightning storm at that time. These radio emissions, called Saturn Electrostatic Discharges (SEDs), were evident by the fact that the signal intensity did not follow the $1/r^2$ decrease with increasing distance of the Cassini from Titan (Fischer & Gurnett, 2011). However, it might have been that a small number of bursts from Titan's lightning were concealed behind those SEDs, and a possibility that HF radio signal is not detectable even when lightning takes place cannot be totally excluded.

Motivation

Titan is fascinating in that it possesses many features that are very similar to Earth. Its surface landscape contains mountain ranges, dunes, and lakes of liquid hydrocarbons such as methane and ethane, given that Titan's average temperature is too low for liquid water to exist. Recent discoveries and study revealed that Titan possesses a complex organic chemistry that can potentially lead to chemical evolution. This raised considerable attention and interest in Titan and the search for lightning since lightning and other discharges can trigger a chemical process that produces biologically important organic compounds. Investigating and understanding the Titan's complex atmosphere, surface, and interior can provide a greater insight and even reform our planetary knowledge.

Mission Objectives

The search for lightning on Titan has been carried out extensively from the many flybys made by Cassini. Although the condition for lightning is favorable, Cassini was not able to acquire any concrete evidence for lightning using the RPWS instrument. Our proposed mission, therefore, will be a big step further in effort to improve the detection of lightning on Titan. Given the broad scope of scientific study possible for Titan, our mission focuses on the search for lightning and detecting and monitoring electrical properties of storms on Titan, which will ultimately provide a new window into understanding the dynamics of atmospheric processes common to all planetary atmospheres. Taking into account the mission cost and science value, we propose a mission to Titan that is composed of three components:

1.) The orbiter: samples the Titan's upper atmosphere and serves as relay station for Earth and the lander.

2.) The lander: equipped with a network of ground-based Time-of-Arrival (TOA) detectors that detects the radio emission arrival time and the source location.

3.) The atmospheric balloon: equipped with the plasma instrument consisting of an Electric Field detector, a spectrometer, and a Langmuir probe that monitors the local electrical properties of the storms on Titan.

Mission Implementation

Our spacecraft is estimated to weigh about 1000 kg. Similar to the Cassini-Huygens mission, our mission's spacecraft will be launched by the Titan IV rocket equipped with a Centaur high-energy upper stage. The exact launch window is not yet determined, but based on the cruise phase time and the synodic period of Saturn calculated in the Appendix A, the next launch window is within 378 days at most from now. The spacecraft should also be launched around sunset to take advantage of the Earth's rotational motion. From the Appendix A, it takes about six years for the spacecraft to insert into Saturn's orbit from Earth using a simple Hohmann transfer orbit. After the orbit insertion, it will begin aerobraking to slow down to a circular orbit over the southern polar region, where the existence of big outbursts of convective clouds has been confirmed and lightning is most likely to be detected (Fischer & Gurnett, 2011). During the reconnaissance phase, the orbiter can descend in Titan's atmosphere to as low as 600 km and observe the condition of the ionosphere, where exciting organic chemistry takes place. Besides being able to extensively sample the upper atmosphere, the orbiter can also make global mapping and measure subsurface structure using a combination of radar altimetry, radio science and remote sensing techniques. The orbiter is equipped with an advanced RPWS instrument that can detect HF radio signals from lightning at two different frequency bands, HF1 and HF2. It also serves as a relay station for data transmission to earth from our landers. This entire surveillance phase in circular orbit will last about two years. With a much longer time of observing with the orbiter, we are likely to detect a concrete signal of lightning on Titan if it takes place.

The Need for Surface Measurements

One of the most common methods of detection of lightning on Earth is via radio wave detection. Using ground-based detectors, radio waves from burst emissions can be detected and, with multiple detectors, even triangulated. Given that Titan has been compared to Earth, it would not be unrealistic to expect to use this method to detect the presence of lightning. Indeed, Cassini was equipped to make such measurements, but as stated above, no such lightning was detected.

The nondetection of lightning on Titan from outside its atmosphere implies a level of difficulty to make such detections from outside Titan. In addition to its visual opacity, the data on Titan's ionosphere and the frequencies of photons it interacts with is somewhat sparse and dependent on theoretical models. While Voyager 1's data showed the potential transmission of 440 kHz, the limited data itself limited the accuracy of current models. This makes orbital detection of Titan lightning via radio emissions somewhat tenuous as it is possible that the actual ionosphere composition is blocking the radio emissions of lightning. In such a case, orbital detection of lightning would be ineffective, possibly explaining the failure of Cassini to detect it. (Fischer, 2007)

The problem of orbital detection is compounded if the Titan's lightning is of a magnitude significantly weaker than that of Earth's, and there is reason to give this supposition credence. When measuring Titan's atmosphere, Cassini's RPWS detected electric fields four orders of magnitude weaker than that of Earth's; as such, the predicted lightning would be four orders of magnitude weaker than that typically detected on Earth. Given that the RPWS did not detect lightning on its passes, and was designed to detect lightning in the MHz ranges, this means any lightning on Titan would be of lower frequency if present. Further, when combined with the possibility of an ionosphere which could absorb lower frequency radio emissions, there is a reasonable assumption that lightning on Titan may be difficult or impossible to detect from orbit. (Fischer, 2007)

A third issue with orbital detection of Titan's lightning, not directly caused by Titan itself, is due to large radio emissions from the Sun and Jupiter. Due to the burst-like nature of some of the emissions from these two large bodies, it is entirely possible for a tool such as the RPWS to detect these bursts and mistake them for signs of lightning on the nearby Titan. As such, in addition to the burdens of making any detection from orbit, any orbital detector will have to deal with lightning-like emissions; this means further having to filter the data and potentially missing emissions from Titan. (Fischer, 2007)

Lander Experiment Proposal

While not concrete, these conditions lead to the decision to include ground-based radio frequency detectors on this mission, in almost exactly the same way as on Earth. Using the topographical map produced from the Cassini's data, a set of small landers will be deployed in an area suspected of having high potential for lightning events. In the case of Titan, this will be around the southern polar area as it shows a high population of convective clouds. Deployment will be aimed at solid ground locations as any locations on a body of liquid would make it impossible to use the particular beacon for precise location of lightning, and that would be inconvenient for the secondary intentions of ground detection. (Fischer, 2007)

The merits of using ground-based lightning detectors on Titan are thus quite straightforward. Within the atmosphere, the problem of potential ionosphere interference becomes negated. In fact, the ionosphere becomes a boon: detecting from the inside, the RF detectors would be somewhat filtered from solar and Jovian burst emissions, cutting out some of the noise for which an orbiter would have to compensate. In addition, a lower intensity radio detector can be used to search for the likely weaker Titan lightning since the Cassini RPWS was designed with a higher frequency target expected. (Fischer, 2007)

The specific type of detectors on these landers will be long baseline TOA sensors. A TOA sensor detects the time at which the radio emission arrives at the sensor. As such, a single detector can detect the presence of lightning, but a network of such devices can actually locate where lightning strikes occur based on the time delay. A network of TOA sensors on Titan would not only detect lightning but also where it occurs throughout this network. Presuming lightning exists on Titan, this would allow for the determination of lightning frequency over the area covered by the network. (Rakov, 2013)

TOA sensors have a few typical configurations: very short baseline, short baseline and long baseline. Given what was learned from Cassini, the very short and short baseline detectors seem like less than optimal choices: very short through short detects in the range of 30 to 300 MHz. Since Casssini's RPWS bottomed out at 50 MHz, these detectors are unlikely to detect Titan lightning, especially if the four orders of magnitude expectation is correct. For this reason, the ground detectors will be equipped with long-baseline TOA sensors. (Fischer, 2007) (Rakov, 2013)

The long-baseline TOA sensors have a detection range of 3-300 kHz, which is far closer to the lightning expected by the electric field detected at Titan. However, in addition to being the right frequency range, long-baseline has another advantage over very short and short-baseline TOA. Both the very short and short-baseline TOAs have a significantly limiting range: only out to a few thousand meters at best for the short-baseline. The long-baseline, by comparison, has a potential range of hundreds to thousands of kilometers. As a result, a network of long-baseline TOA sensors would allow coverage of a large fraction of Titan. (Rakov, 2013)

Aiming for the 1000 km range on a single detector, this provides coverage of over 3 million square kilometers. From this coverage area, the use of only 6 landers will provide coverage of over 22% of the surface area of Titan without overlapping. Deploying this across the southern polar region should give the detectors the maximum opportunity to detect the presence or absence of lightning. However, without overlapping, the detectors will not be able to triangulate radio emissions from lightning. As such, the mission will require a dozen detectors in order to get a large coverage area as well as the capability to locate signals.

Figure 1 below gives an example of how detection using a TOA system works. A hyperbola is formed between two sensors by detecting a bolt, showing the arc of potential locations of the strike. As a result, a bolt must be detected by at least three sensors to determine the specific location of a strike. As a result, this reinforces the need for significant overlapping between landers: if at least three detectors sense lightning, they can identify the general location before accounting for sensor error. Given that, on Earth, cloud to cloud strikes tend to have lower intensity than cloud to ground strikes, the determination between cloud strikes and ground will depend on the difference in intensity. Since cloud discharges have about 10% the energy of ground strikes, the frequency of the discharge should be effective in determining the type of strike.

Given that this expedition intends to include atmospheric balloons as well, the thought of integrating radio detectors on the balloons may seem like a way to avoid the need for the landers at all. However, the use of the TOA sensors on the ground is preferable to this option for several reasons. The first and most obvious reason is that using the balloons to detect lightning would only give a relative location of any strikes instead of a more absolute location. Secondly, the landers will be used to provide location telemetry for the balloons, offering the ability to collaborate data from the instruments on the balloons with relative locations on Titan.

Twelve landers may seem excessive; however, the lander design is actually quite simplistic. Aside from the TOA sensor and antenna, the only other requirements for the lander are a transmitter to send data to the orbiter. In addition, the landers do not require the ability to move beyond adjusting themselves upon landing and some sort of stabilization. This means that each lander should not be particularly complex and should also allow the landers for this mission to be significantly smaller and cheaper than typical full-mission landers such as the Martian rovers. The reduction to the weight of the overall mission should justify the use of so many landers.

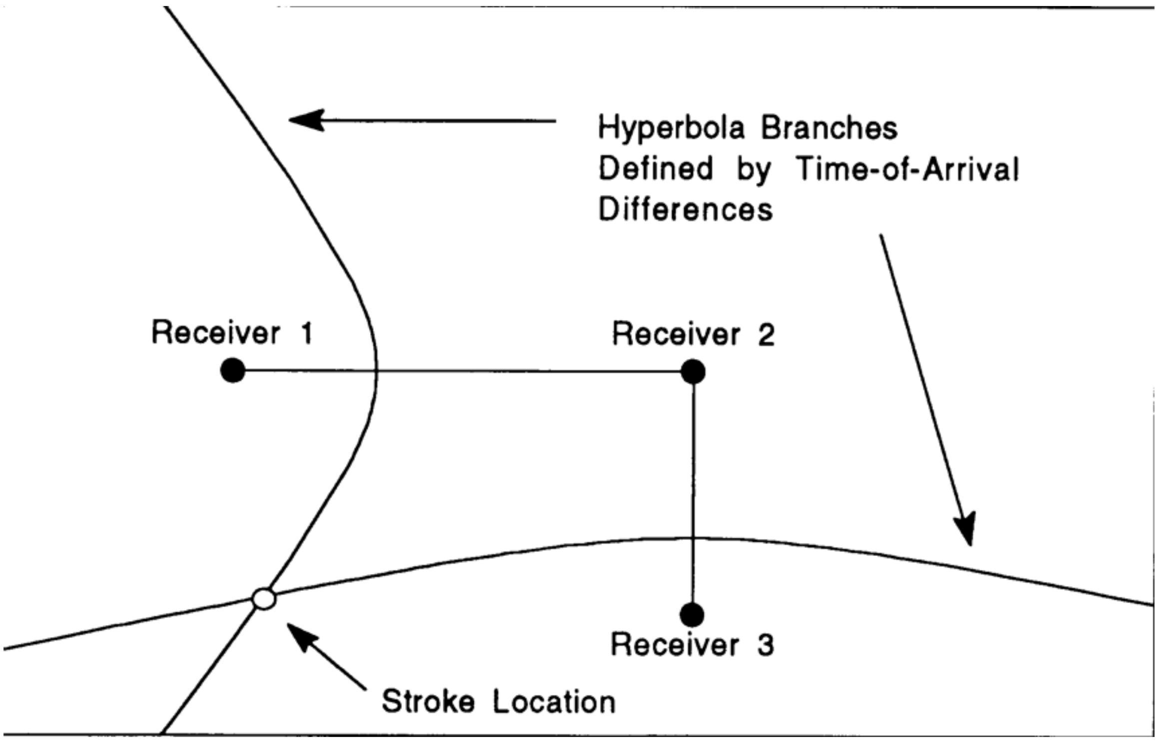

Fig. 1: Visual Representation of Time-of-Arrival Sensors

In addition to just detecting lightning, the ability to triangulate lightning strikes provides an opportunity for greater scientific study as well. By detecting, recording and mapping out the location of lightning strikes, a general pattern of frequency in lightning strikes across the mapped area can be determined. With a pattern of strikes mapped across a portion of the moon, a model of Titan's weather and cloud patterns can be established, and later missions can be planned around these models.

In terms of performance for this type of detection, it is necessary to look at the performance of other long-baseline TOA networks. The U.S. Precision Lightning Network covers the continental United States and more with over 100 sensors. The system reports greater than 90% efficiency at detection and an error in location of about 250 m. Due to using fewer sensors, the network created on Titan cannot presume the same level of efficiency and accuracy in location, but it should be more than efficient to detect and identify the general areas of lightning activity on Titan.

Even if Titan does not have lightning as Earth does, there is still a possibility that other kinds of discharges may exist within the Titan system, including haze layer discharges. While it may be too weak for the ground detectors to pick up, their presence within the ionosphere means a higher possibility than detection from orbit. (Fischer, 2007)

The simplicity of the detectors themselves will necessitate that either the orbiter or mission control take the detector data and process it through the algorithms necessary to define the locations of detected lightning. Though the rate of discharge on Titan is difficult to predict with the assumptions described above, having the orbiter parse and associate some of the data before sending it to Earth seems wise, especially considering that Titan will have periods of radio blackout when Saturn is between Earth and said moon.

Balloon Experiment Proposal

The landers instantiate a network of detectors for determining the location and intensity of lightning events on Titan. This gives us a good map of electrical activity, but does not tell us much about the processes occurring in the clouds. In order to get this information, we propose the addition of a weather balloon component to the mission. These balloons will be fitted with a plasma instrument consisting of an Electric Field detector and a Langmuir probe, the combination of which serves to give us data on the local electrical properties of the storm. The addition of a spectrometer to the balloons will complete the instrumentation such that we are able to determine the characteristics of the cloud plasma. In the event of lightning detection on Titan, this will serve to give us more information about the origins of this lightning, and how its formation differs from lightning on Earth. On the other hand, if lightning is not detected, we can use these balloons to determine why lightning isn’t happening.

This secondary mission serves to guarantee data acquisition in the event of the failure of the primary mission. It may be the case that there are no lightning events on titan, and the landers’ RF detection network will not see any signals. Even if there is no lightning detected, we want to try to learn how close the system is to achieving lighting. This can tell us, for instance, if there may have been lightning on titan in the past. One could imagine that before titan was able to cool to its current temperature, the increased atmospheric energy could have been enough to spark lightning. By looking at the electrical properties of the clouds, we can tell if lightning is impossible, or merely improbable.

After the successful landing of each of the primary probes has been confirmed, each probe will release a weather balloon. These balloons will be inflated from a tank of liquid helium. Once filled, the tank will detach and the balloon will begin to rise into the cloud layers. Once arrived, we can begin to monitor the local properties of the storms.

Because there is very little light available to use for solar energy, and we wish the mission to last longer than the few hours afforded by a battery, another form of energy production must be used. Wind speeds on titan vary between 10-40 m/s in the altitude of interest. [6] By putting a wind turbine on the balloons, this power can be harnessed. In general, the balloon will simply be moved along with the wind currents. However, any time the wind changes direction there will be a time in which the balloon has not yet accelerated to match the change, and during this time there will be a relative velocity between the balloon and the wind that will be used to charge the batteries. It is likely that the current generated by this method will be fairly low, so this can be considered a "trickle charge" method. This leads to a nominal mission plan that involves periods of sensing alternating with periods of charging.

The plasma instruments on the balloons will be fairly similar to the RPSW instrument on the Cassini Spacecraft. Primarily this will consist of an Electric Field Detector and a Langmuir probe. We know that there is a critical charge separation that must be reached in order for the electric field to be strong enough to ionize the atmosphere and spark a lightning event. The electric field detector will serve to tell us how strong that field is actually getting. But, in order to determine the critical field needed to produce lightning, we need more information. This will be provided by the Langmuir probe and spectrometer.

A Langmuir probe consists of a conducting sphere which is charged to an electrical potential relative to the local plasma potential, a value which can be determined from the Electric Field detector. The Langmuir probe thus generates an electric field in the space surrounding it. This serves to attract charges from the local medium. These charges form a current into or out of the device. By varying the potential of the probe, it is possible to produce an I-V curve which can be used to determine the local density of charge carriers in the cloud. (Conde, 2011)

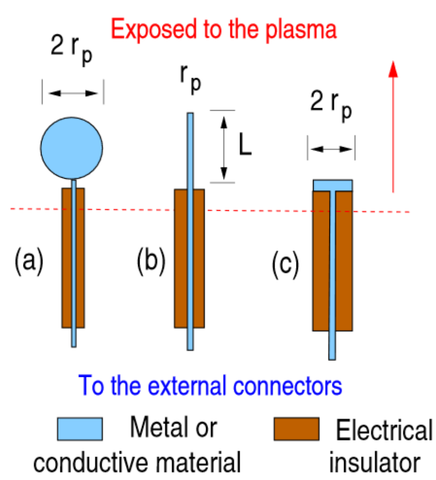

Figure 1: Collecting Langmuir probes with radius r_p and (a) spherical, (b) cylindrical and (c) planar geometries.

Once we know the charge carrier density, we need to use the total local density of the cloud in order to determine the degree of ionization of the plasma. The onboard Spectrometer is used to give us a measure of this density. The degree of ionization is then simply the ratio of ionized to neutral particles. If the clouds are too strongly ionized, it may be that they are able to dissipate any charge buildup before it can build to such a level as to produce lightning.

Lightning is sparked when charged particles are accelerated in an electric field such that when they hit a neutral particle there is enough energy involved to ionize the particle. This happens if the mean free path of charged particles in the cloud, multiplied by the electric field present along that path, is longer than a critical threshold. The ionization energy is known from quantum mechanical considerations of the species involved in the collision, which we are able to gain by looking at what species are detected by the on board spectrometer. Knowledge of the species present also serves to tell us the cross section of interaction for these collisions. Coupled with the now-known density of particles, we are able to solve for the mean free path of these collisions. The electric field is directly measured, and using all of this information we can calculate the average energy of charged particles colliding with neutrals in the cloud and compare it to the ionization energies of the species involved.

The unfortunate limitation of this technique is that we are only able to determine average particle energy in the immediate surroundings of the balloons. This means that the drop point of the landers needs to be carefully considered such that the balloons have a high probability of entering a storm system. Additionally, even if the balloon is in a cloud of interest, it does not measure the maximum average particle energy, but just that of the particles in one part of the cloud. This means that we are actually measuring the *lower bound* for cloud particle energies. This limitation is partially mitigated by the use of many probes. Also, as the probes move through the clouds, it is likely that at least one of them will pass through a region of maximum particle energy.

While the plasma instruments on the balloons are capable of providing local information on the electrical properties of the storms, they do not have any ability to know their own position in space. In order to gain this information, each balloon will transmit its data omnidirectionally. This signal will be received by the lander detection-network. These time-of-arrival sensors are already purposed to triangulate the position of lightning strikes, and will serve to give us the ability to locate the positions of each of the balloons. This can then be correlated with readings from the orbiter to determine if the balloon is in or around a cloud system. In addition, by looking at the redshift of the transmission, we are able to gain large scale wind speed information at the location of the balloon.

The balloon mission will serve to tell us the average particle energy of charges in Titan’s clouds as compared to the ionization energies necessary to produce lightning. This will give us a new window into the electrical dynamics of weather on Titan. This approach has the additional virtue of providing spectroscopic data regarding these clouds, which can be later mined for additional information by other groups.

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Conclusion

Titan is a complex body that somewhat resembles our planet Earth and potentially offers many exciting scientific discoveries. The detection of lightning on Titan would be one of much import for scientists. The study of lightning in an earth-analogous atmosphere offers a fruitful avenue of research to better understand our own atmosphere. This proposed combination of orbiting and in situ measurements will provide a thorough observation and a tremendous amount of scientific knowledge about Titan that can potentially change our current understanding of atmospheric dynamics.

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Appendix A

Assume circular orbits for Earth and Saturn, the time it takes to reach Saturn from Earth using a simple Hohmann transfer orbit can be calculated with Kepler's third law of planetary motion.

Earth's semimajor axis = 1.00000083 AU

Saturn's semimajor axis = 9.5428244 AU

Spacecraft's semimajor axis during Hofmann transfer orbit:

a = (1.00000083 AU + 9.5428244 AU)/2 = 5.2714126 AU

Total flight time:

$t = \frac{\sqrt{a^3}}{2} = \frac{\sqrt{5.2713126^3}}{2}$ = 6.05 years

The synodic period of Saturn can be calculated as followed.

Earth's orbital period = 1 yr

Saturn's orbital period = 29.46 yr

Synodic period = $\frac{29.46*1}{29.46-1}$ yr = 1.035 yr = 378 days