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Landings Throughout the Solar System

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ABSTRACT

The valuable *in situ* observations provided by landers and probes are a primary way we learn about other environments in our Solar System. This paper will discuss the successes and failures over the years in human kind's attempts to land spacecraft on objects in the Solar System, excluding the Moon. From the first successful lander, Venera 7 on Venus, through to the recent triumph of the Mars Phoenix Lander, this paper will detail the changes in lander design and technology as well as analyzing high-priority future missions. Because the current focus of Solar System exploration is detecting signs of life, future landers should be equipped with more surface penetration capabilities and microscopes. Lander missions to Europa and Enceladus should be a future focus for expanding the search for signs of life in the Solar System.

Subject headings: comets: individual(67P/Churyumov-Gerasimenko) — minor planets, asteroids — planets and satellites: individual(Enceladus, Europa, Jupiter, Mars, Phobos, Titan, Venus) — solar system: general — space vehicles — space vehicles: instruments

1. Introduction

Exploration of the Solar System advances through the progression of flyby, orbiter, lander, rover, and then human missions. This is how human kind went to the Moon and how NASA is currently progressing to sending a human to Mars. Landers represent a critical leap in this road of discovery because they provide the first opportunity to experience these foreign worlds in any direct way. There are many characteristics of which we cannot be certain until we actually send something to visit the environment. Remote observations, either Earth-based or from spacecraft flybys or orbiters have extremely limited results; landing a spacecraft on a Solar System object is one of the best ways to observe directly that environment.

In situ observations, observations made directly at the actual location, provide crucial information about the geology, geochemistry, and geophysics of the area (Basilevsky et al. 2007). A thermometer on the spacecraft can measure temperature, a magnetometer can measure the magnetic field, and the spacecraft can do on-board analysis of the surface composition with a mass spectrometer or by performing electrical and thermal conductivity measurements. The *in situ* spacecraft can also give scientists a better idea about atmospheric structure and composition either by doing on-board observations with a mass spectrometer or by having scientists analyze how a radio signal sent from the spacecraft was attenuated on its journey back to Earth (de Pater & Lissauer 2001).

In the first stages of planetary exploration, Venus was the prime target because it was thought to be a twin to Earth and hospitable to life with a protective atmosphere. Landers, orbiters, and flybys made it clear that is not the case. As a result, lander missions searching for signs of life are now focused on Mars, a planet once thought to be more dead and barren due to the lack of a substantial atmosphere.

The type of lander and the requirements of the mission depend largely on its destination. The characteristics of the environment the spacecraft will encounter determines what sort of protection, if any, the lander and instruments will need. The length of the mission and the cruise time and distance dictate what sort of power source is appropriate. As technology improves, landers and their instruments become more advanced, which leads to more detailed *in situ* observations. However, increased complexity of lander technology requires more testing, causing an increase in cost. This paper will touch on some of these considerations.

Humans have already followed the progression of discovery to its completion for the Moon, therefore exploration of the Moon will not be discussed here. Instead, the paper begins with the Soviets and Venera 7, "the first spacecraft that safely reached the surface" (Titov et al. 2002) of another planetary body, in this case Venus, on Dec 12, 1970.

This paper considers a lander as any spacecraft designed to land or touchdown on another object in the Solar System and transmit data from that location, or a spacecraft that executed a landing on a foreign object, despite not being designed for such a purpose. To be considered a successful landing, the spacecraft must transmit data from the surface of the Solar System object.

2. Motivation

I am excited to have the opportunity to research and write this paper because I have always wanted to learn more about planetary missions in the Solar System. There have been so many different missions sent out by different countries that it is difficult to keep them straight without detailed study. What mission went where and why? I am only focusing on landers, which represent a small subset of all Solar System missions. However, because many lander missions were done in conjunction with other missions (such as orbiters), I will have exposure to more than just landers while researching this paper.

Secondly, I am very interested in instrumentation, but I have never had an opportunity to gain any experience in space-based instrumentation. I know that expanding my horizons and learning more about this extremely important field will help me in the future.

I was drawn to landers rather than flybys, orbiters, or rovers because landers are the first opportunity for direct observations of an environment. I think this fact makes them very interesting and pushes the development of their technology. Also, I find it intriguing that they come in so many different shapes and sizes and require extreme tailoring to the expected environment, leading to complex engineering challenges. Based on my limited knowledge, it seems there is more similarity between the spacecraft for different missions when designing flyby crafts and orbiters, so I did not think it would be as interesting to analyze them.

3. Types of Landers

The four basic types of landers discussed in this paper are atmospheric entry probes, pod landers, legged landers, and small-body surface missions. As may be clear, the landers are divided into groups based on "the way in which they encounter an atmosphere or surface" (Ball et al. 2007). These categories also represent, roughly, the development in lander technology over time.

Atmospheric probes are not designed for purposes of landing, but rather the spacecraft's "design is driven by its mission in the atmosphere" (Ball et al. 2007). They may land, as in the case of the Huygens probe on Titan, but atmospheric probes do not have dedicated landing gear, leading to a simpler design in some ways.

The next level of complexity are pod landers, spacecraft designed specifically to land, but the orientation of the spacecraft once it has landed is insignificant. Pod landers often inflate airbags before landing, and then bounce and roll along the surface until they stop naturally. The airbags then deflate and the lander unfolds, positioning itself upright in the process. Beagle 2, the British mission to Mars, is an example of a pod lander. Obviously, pod landers require more complex engineering than atmospheric probes and more moving parts, which are used very sparingly on unmanned spacecraft.

Legged landers, or planetary landers with dedicated landing gear, must land upright and often use retro-thrusters to slow the spacecraft during the last part of its descent and control the landing. The recent Phoenix lander on Mars was the first successful legged lander since the two Viking landers on Mars in the 1970s.

The last category of landers, those for small-body surface missions, are very different from the rest because they function in an environment with low surface gravity. Therefore, the spacecraft cannot use the force of gravity to assist in landing as it can for atmospheric probes, pod landers, and legged landers. However, the low gravity does mean that the spacecraft can fly right up to the surface and hover over it while performing *in situ* observations without truly landing on the object's surface, or the spacecraft can execute a landing with a very low and controlled incoming velocity. A downside to the low gravity situation is that the force keeping the spacecraft on the surface is not very strong, so it is remarkably easy for the spacecraft to bounce back off of the surface. To remedy this problem, many small-body surface missions anchor themselves to the surface after landing, just as the Rosetta Lander Philae plans to do when it lands on its target comet in 2014.

4. Setting the Stage for Planetary Landers

Planetary exploration in the Solar System was successful for the first time in 1962 with the American Mariner 2 flyby of Venus. Though all Soviet attempts at this time had failed, they were still competitive with the USA in the race for planetary exploration. Both the Soviets and the USA had launched successful Lunar impacts and landings. It is interesting to note that the first target of landers, in this case atmospheric probes, was Venus. The Soviets were attempting to send atmospheric entry probes to Venus before either they or the USA tried to send landers to the Moon. Figure 1 shows lander destinations based on the year the lander was launched and the country or countries that provided the primary funding for the lander. The launch date is more important to consider than the landing date because the launch date indicates the era of the technology on the lander. Even though the Galileo atmospheric probe conducted its mission in 1995, its technology was from the mid-1980s. Tables 1 and 2 provide detailed information about each lander discussed in the paper.

5. Early Landers (1970 - 1989)

Many of the early programs, especially the Soviet's Venera missions to explore Venus, "were successful because they developed spacecraft and payload 'families' with step-by-step modifications between launches" (Titov et al. 2002). For instance, the Venera 4 thru 8 atmospheric probes were all of the same basic design, but minor tweaks were made to each one, making them "progressively more sophisticated and optimized to survive the Venusian temperature and pressure environment all the way down to the surface" (Ball et al. 2007). Still, Venera 4, 5, and 6 remained only atmospheric probes (as designed) and were destroyed by the pressure and temperature before reaching the surface of Venus. Venera 7 was the first probe to make a soft landing and transmit data from the surface of another planet, even though it was still an atmospheric probe in design. Venera 7 had several instruments, but only the data from the temperature and pressure sensors were sent to Earth (Basilevsky et al. 2007). Venera 8 was also essentially an atmospheric probe, but it was equipped with modified antennae to ensure it would still be able to communicate "if the probe did not come to rest in an upright position" on the surface of Venus (Ball et al. 2007).

Venera 9 thru 14 were true landers with a legged lander design. Each pair (9 & 10, 11 & 12, 12 & 13) were basically twins and more complex than the previous pair. All had panoramic imaging devices, but the camera cover malfunctioned on Venera 11 and 12, so no pictures were taken. Venera 13 and 14 also had drilling capabilities, enabling them to collect a few cubic centimeters "from the top few centimeters of the surface material" that was then analyzed on-board (Basilevsky et al. 2007).

The American answer to the Soviet Venera missions was the Pioneer Venus mission. NASA began planning Venusian atmospheric probes in the late 1960s, right around the time the Soviets were beginning to have success with this type of mission. The USA, however, had not yet flown atmospheric probes. The Pioneer Venus mission consisted of four atmospheric probes- one Large Probe and three Small Probes- that were launched and cruised to Venus together on one Multiprobe Bus spacecraft. Once the Multiprobe Bus arrived at Venus, it released the Large Probe and then, four days later, released the three Small Probes simultaneously in a "frisbee-like" fashion (Bienstock 2004). The releases were planned in such a way that all four probes began their entry and descent into the atmosphere within minutes of each other at very different locations around the planet- the Large Probe near the equator, the North Small Probe at a rather high latitude, the Day Small Probe at a mid-southern latitude on the daytime side of Venus, and the Night Small Probe at a mid-southern latitude on the nighttime side. Despite being designed strictly as atmospheric probes, the Day Small Probe "transmitted from the surface for over an hour...before battery depletion and temperature increases above the electronics operating point caused the transmitter to cease operating" (Bienstock 2004). The primary engineering challenge of these probes was designing them in such a way that they could withstand the extreme temperature and pressure conditions during entry, descent, and on the surface- "surface temperatures in excess of 450 °C and surface pressures at roughly 100 Earth atmospheres" (Bienstock 2004). Both the Large Probe and the Small Probes had an enclosed pressure vessel with diamond and sapphire windows for the viewing instruments and tiny inlets for the sensing instruments.

The Galileo probe to Jupiter, launched October 1989, was similar in design to the Pioneer Venus Probes. Technically, the Galileo Probe could be considered only an atmospheric probe, and not a true lander. However, because Jupiter does not have a solid surface, the distinguishing factor between a lander and an atmospheric probe is not clear. The Galileo probe was the first spacecraft to use $LiSO_2$ batteries, making them flight tested. They have since become the standard for short duration missions and $LiSO_2$ batteries were used on the recent Huygens mission to Titan.

The Soviet Mars 3 mission, a pod lander, became the first spacecraft to successfully land on the red planet in December 1971. However, the mission itself was not particularly successful because it only transmitted data for 20 seconds before the lander inexplicably went silent. There is a chance that the spacecraft landed during a very strong dust storm, causing damage to the lander. This theory is based on the fact that the fragment of a photograph received before Mars 3 went silent was very faint, possibly due to a dense cloud of dust.

NASA's Viking 1 and 2 landers were the first successful legged landers to land on Mars (1976), and Viking 1 still holds the record for the longest mission on the surface of Mars at nearly 6.5 years. The cameras on the landers "set a high standard for excellence" (Smith et al. 1997) and their meteorological observations "ha[ve] not been rivaled" (Ball et al. 2007). The landers were also equipped with scoops and instruments to analyze the soil. It was a truly remarkable mission and "many Viking developments have yet to be improved upon" (Ball et al. 2007).

The Vega missions were actually missions to Halley's comet, but they passed by Venus on the way, dropping off both surface landers and atmospheric balloons. The surface landers were similar to Venera designs, but they landed on a completely different part of Venus, only accessible due to the mission trajectory to Halley's comet (Basilevsky et al. 2007).

The Soviets, supported a bit by some European countries, launched a small-body surface mission to Phobos, a moon of Mars, in July 1988. This mission was to include two landers and a mobile, hopping robot. Shortly before the landers were to be released, contact with the spacecraft was lost permanently and the entire mission was lost.

6. Recent Landers (1990 - 2008)

After the launch of Galileo in 1989, new Solar System exploration by means of landers went through a bit of a hiatus until the late 1990s, when launches of the new generation of landers began. The most noticeable difference between the early landers and these more recent landers is the shift in lander destinations. No new missions were sent to Venus and the focus changed to Mars. There were also several more small-body surface missions, and even a mission to Titan, a moon of Saturn.

6.1. Mars

Both NASA and Russia attempted to end the lander drought in 1996 with landers destined for Mars. In April, NASA launched the Pathfinder mission, which contained both a lander and the very small Sojourner rover. The main purpose of the mission was an engineering demonstration: to provide an example of a low-cost lander and to deploy and support a rover. Pathfinder is a prime example of the faster, better, cheaper model for low-cost space exploration (Ball et al. 2007), though it was the second such mission launched by NASA. Arriving 20.5 years after Viking, Pathfinder was the first surface mission on Mars since the Viking Landers. The Viking Lander cameras were so impressive that, despite the Pathfinder cameras being "lighter, more capable, and vastly cheaper,...the final pictures will look qualitatively similar to those of Viking" and even the resolutions are comparable (Smith et al. 1997).

The Russian mission, Mars 96, was a very ambitious mission containing an orbiter, two landers, and two surface penetrators. However, during launch the second burn of the fourth stage rocket failed and the spacecraft never reached the required escape velocity to leave Earth. The two Small Stations, or landers, would take networked observations for a year with instruments for, among other things, seismic observations and meteorology. France, Germany, and other European countries contributed to instruments on the mission.

Mars Polar Lander (MPL) was an unsuccessful legged lander mission, launched by NASA in January 2009, and destined for the South Polar region of Mars. Two surface penetrators (the Deep Space-2 Mars Microprobes) rode out to Mars on the same cruise stage as MPL, but they were not technically a part of the lander. The last communication with the cruise stage, containing MPL and the surface penetrators, was just before entry into the Martian atmosphere. Many of the instruments designed for MPL ended up successfully traveling to Mars several years later on the Phoenix lander.

The Beagle 2 was the British built lander component of ESA's Mars Express Orbiter mission. Named for Charles Darwin's ship that took him to the Galapagos Islands, leading to the discovery of evolution, Beagle 2 traveled to Mars to search for life. It was to be the smallest Martian lander, developed at very low cost, but had "the highest payload/gross mass ratio for a planetary lander" (Ball et al. 2007). Beagle 2 had an impressive suite of compact life detecting instruments, including a small 'mole' tool that travels below the surface, collecting samples to bring back to the lander for on-board analysis. Sadly, no communications were ever received from the lander after it detached from the orbiter and it is not known whether Beagle 2 ever touched the surface of Mars.

The most recent lander mission was the Phoenix Mars Scout, destined for the northern plains region of Mars with the main purpose of analyzing the water-ice-rich soil discovered in the area by the Mars Odyssey orbiter. A large amount of time and money was saved by using the fully constructed lander platform from the cancelled Mars Surveyor Program 2001 Lander and by reusing much of the instrumentation from both the 2001 Surveyor Lander and the failed Mars Polar Lander. Phoenix has a robotic arm that digs through the soil and delivers samples for on-board analysis with a microscope and an electrochemistry analyzer. Phoenix also has imagining and meteorological capabilities. The mission length is limited to three months due to the far northern landing site. Phoenix landed just before summer solstice in the Martian northern hemisphere, but by the end of the summer there was not enough direct solar radiation to keep the lander powered.

6.2. Titan

ESA's Huygens probe, launched October 1997, traveled to Titan on NASA's Cassini Orbiter. Designed as an atmospheric probe, Huygens would sample the atmosphere during its 2.5 hour descent and take images at lower altitudes, but it was not known whether the probe would survive impact with the surface of Titan. The probe did survive the impact and landed on a "relatively flat and solid" surface (Lebreton et al. 2005). Huygens transmitted data from the surface for at least 70 min, until Cassini, which acted as a relay for the signal to Earth, dropped below the horizon and out of the view of Huygens. It is thought that the mission probably lasted 17 min longer, until the $LiSO_2$ batteries became fully discharged

(Lebreton et al. 2005).

6.3. Asteroids

In February of 1996, NASA launched the NEAR-Shoemaker spacecraft, which set off to the second-largest Near-Earth asteroid, Eros. This mission was the first of NASA's low-cost exploration missions to launch. It cannot really be called a lander mission, because NEAR-Shoemaker was designed solely as an orbiter. Only at the end of the mission (February 2001), after the spacecraft had orbited Eros for almost a year, did scientists decide to attempt landing NEAR-Shoemaker on the surface of Eros, even though the spacecraft was not designed for such maneuvers. The primary reason for executing the landing was to obtain high resolution images of the Eros surface, which was successful. The mission lasted 14 days on the surface and collected wonderful gamma-ray spectroscopy data, much better than the data collected from orbit (Dunham et al. 2002).

Hayabusa, launched May 2003, is an interesting Japanese small-body sample-return mission to the asteroid Itokawa. Hayabusa also carried a small hopping mini-rover MINERVA, but it is believed to have floated away after being released, and never encountered the asteroid surface. However, the Hayabusa spacecraft itself descended to the surface and perfomed two touchdowns. During the touchdowns, Hayabusa was to fire a projectile into the asteroid and use a collection horn to capture some of the debris. This sample was then transferred into a sealed canister for transport back to Earth. Sensors apparently cancelled the projectile firing during the first touchdown, but the collection horn did scrape the surface of the asteroid. It is unclear whether any of the small particles collected in the horn simply by scraping the surface would have made it into the sample canister. During the second touchdown, Hayabusa sent the command to fire the projectiles, but it is not certain if the command was executed. The second canister may or may not contain a surface sample. The spacecraft is due to return to Earth with the samples in June 2010 (Yano et al. 2006).

6.4. Comet

The Rosetta Orbiter with its Philae lander launched March 2004 and is currently *en route* to the comet 67P/Churyumov-Gerasimenko. Philae plans "to make the first ever controlled landing on a comet nucleus" in November 2014, when the comet is around 3 AU. The lander will have a 5 day initial operation, and then transfer over to an extended mission (∼3 months) "until the comet reaches 2 AU heliocentric distance" when the lander is expected to overheat (Ball et al. 2007). Instruments on the lander include imagine equipment, microscopes, spectrometers, and a drill, to name a few.

7. Future Landers (2009 and on)

Few landers are currently in the design phase and landers are often the first part of a mission to be cancelled when budgetary situations change. ESA was sending a lander to Mercury on their 2019 BepiColombo mission, but it was cancelled for budgetary reasons. The Russians are supposedly launching Phobos-Grunt, another attempt at a small-body surface mission to Phobos, at the end of 2009, but many critics think it will not launch until the next launch opportunity in 2011. Phobos-Grunt is currently the only planetary lander affirmatively under development.

7.1. Low-cost, Focused Lander Missions

The future of planetary exploration with landers relies on small, low-cost, highly focused missions targeting specific questions. The current Mars Scout program (of which Phoenix was the first mission) is a promising model. The Mars Scout program is a series of small, low-cost missions designed to quickly respond to a "compelling" scientific discovery (Garcia & Fujii 2007). They are selected from proposals submitted by the academic community and then led by that Principal Investigator, but supported by JPL and other partners. These smaller missions do not take the place of the large NASA missions, but rather provide a means of further investigation of discoveries made by the larger, longer term missions. For example, Phoenix was developed to respond to the discovery of water ice in the Martian north polar region made by the Mars Odyssey orbiter (Garcia & Fujii 2007).

It is very important for the missions to be strong collaborations between space agencies, academia, and industry, as with the Mars Scout program. This collaboration divides the financial burden and allows different parties to contribute resources that have already been designed and/or tested. Much of the design, payload, and some hardware for Phoenix came from the Mars Surveyor 2001 lander, which had been cancelled for budgetary reasons, and the Mars Polar Lander, which never regained contact after entry into the Martian atmosphere. The recycling of knowledge and designs is a huge cost and time saver.

The low-cost, small, and focused missions will come to play an invaluable role in planetary exploration. By being a cooperative effort with academia and industry, they preserve valuable space agency funds for the larger, longer term missions. The smaller scope missions also fill in the observational gaps left by the larger missions, providing a better understanding of the environment. The deeper knowledge of the environment enables scientists to better plan the next exploration mission.

7.2. Searching for Life

A main focus of human kind is discovering if life exists in places in the universe other than Earth. Landers are the first step in the progression of planetary exploration that can truly explore other worlds and search for signs of life through *in situ* observations. Currently, based on our understanding of life, the intriguing candidates on which to search for life are Mars, Titan, Europa, and Enceladus. It is a long process to explore an entire world one specific location at a time and for only a relatively brief period at a time. Human kind has been chipping away at Mars since the Viking landers in the mid 1970s. The Huygens probe to Titan was the first step in direct investigation of that environment, and now those discoveries, along with data from the many Cassini flybys, can be used to drive future, more complex, targeted, and longer duration lander missions to the moon of Saturn.

Europa is a very enticing location based on what was seen by Galileo during flybys. With its water ice, probable subsurface ocean, and tidal heating, Europa is a prime candidate for water-based life. Future lander missions to Europa should be a high priority, and it is surprising there has not been more extensive discussion of this. Abelson & Shirley (2005) proposed a Europa lander as part of the Jupiter Icy Moons Orbiter mission, but it was not incorporated into the design, and this entire orbiter mission ended up being cancelled in 2005.

After Cassini flyby observations, Enceladus arose as an enticing lander destination. A lander along the tiger stripes would be an incredible opportunity to search for extremophiles living amongst the water vapor and methane plumes. No such mission has been mentioned, but that could be due to the fact that the Cassini observations are still new and more flybys are planned in the extended mission. Designing a lander mission to Enceladus might be premature because each of the on-going Cassini flybys paints a better picture of the environment on the moon. Therefore, once those observations are concluded, scientists and engineers will have a better understanding of the requirements and goals of an Enceladus lander mission, and planning can begin.

7.3. Networked Landers

Future missions should use multiple networked landers deployed across the surface of Solar System objects to get a better idea of the overall environments instead of just sampling one specific place at a time. The networked lander idea has been proposed several times, but has yet to be tested. The ill-fated Mars 96 mission included two networked surface stations providing simultaneous observations. NetLander, a set of 4 low-mass landers, was planned to launch in 2007 and make networked observations on Mars for a year, including seismic measurements, but the mission was cancelled in 2003 (Larmat et al. 2008).

Mars 2016 is a NASA concept currently under study and could include a network of three to four long duration landers. The landers would include instruments for geophysical and meteorological observations. The National Research Council listed the concept as high priority in their Decadal Survey, indicating networked landers should be a focus of future American planetary exploration (NASA 2009).

Data from seismographic instruments on networked landers on Mars would provide a much more clear model of the interior of the planet than is currently available. Seismometers were sent to Mars on the Viking landers, but turned out not to be sensitive enough to detect any quakes. More sensitive seismometers have been proposed, and some were even included on the landers of the Mars 96 mission that never left Earth.

7.4. Instrumentation on Future Landers

The focus of future instrumentation should also be driven by the goal of detecting signs of life in other parts of the Solar System. Most scientists believe that single-cell extremophile microbes probably exist other places in the Solar System, not only on Earth. Therefore, the instrumentation on landers should target environments that might be hospitable to such organisms and the instrumentation needs to be sensitive enough to detect the existence of a single-celled organism.

One instrumentation focus should be surface penetrators because, for example, microbes could potentially survive below the surface of Mars, using the layers of soil above them for protection against radiation. Several current generation landers have had this capability, but the most advanced versions never completed their missions. In addition to the two Small Station landers, Mars 96 also carried two identical rather sophisticated surface penetrators with ten experiments of their own. These, of course, never made it to Mars. The Mars Polar Lander also carried two surface penetrators, the Deep Space-2 Mars Microprobes, but these were lost with the MPL. The Beagle 2 lander had a flexible burrowing tool that could travel under the surface and collect samples to bring back to the lander for analysis. This robotic mole is a different sort of surface penetrator than the previous ones mentioned, but it still serves the valuable function of boring down where microbes could live and collecting samples. However, this technique was not tested either because the Beagle 2 lander never communicated with Earth.

Microscopes capable of detecting and imaging microbial life forms should also be a focus of future landers. Beagle 2 carried such an instrument, but it was lost with the lander. Phoenix had a microscope for examining the detailed structure of soil samples, with a resolution of about 10 nm (NSSDC 2009). Continuing to send these types of instruments and more powerful microscopes will better enable the search for signs of life.

8. Power Considerations

Power generation is a critical component of any method of Solar System exploration, be it flybys, orbiters, landers, rovers, or explorations by humans first-hand. With any unmanned exploration spacecraft, humans generally cannot service or resupply the spacecraft after it has been launched. Therefore, the spacecraft only has access to items sent with it into space. This means that, no matter how well engineered the spacecraft is, its lifetime is limited by how much power it can access. Probes such as Pioneer, Galileo, and Huygens, only need power for the relatively short duration descent, but those batteries need to remain charged during the journey from Earth until they are activated when the probe disconnects from the orbiter. For longer duration missions, such as the current generation of Mars landers, solar panels are a good option because it enables the lander to generate its own power, therefore reducing the required launch mass.

Not surprisingly, the energy requirements of the mission determine what sort of power source is suitable. Low energy requirement missions generally only operate for a short period of time, "within a few hours or days," such as the atmospheric probes mentioned above (Ball et al. 2007). The probes used in these short duration missions are mostly powered by on-board batteries.

However, most planetary exploration spacecraft have high energy requirements because they operate for longer than a few days. For these higher energy requirement missions, there are two approaches to power. Firstly, instead of launching the spacecraft with an on-board energy source, the spacecraft can "extract energy from the environment" in the form of solar energy or even wind energy in the case of Mars (Ball et al. 2007). The spacecraft can then convert that energy into power. The second option is simply to provide the spacecraft with "an energy source that has a higher energy density (watt-hours per kilogram) than" batteries with regular chemical storage (Ball et al. 2007). The primary example of a higher energy density energy source are radioisotopes. A pictorial representation of the ideal power source for a given mission duration and energy requirement is shown in Figure 2.

8.1. Batteries

As mentioned above, spacecraft with very short duration missions have low energy requirements, making them prime contenders for an on-board energy source such as a battery. Batteries are a means of storing chemical energy that can then be converted into electrical power. There are two types of batteries: primary batteries and secondary batteries. Despite what one might think from the names, they are not 'main' batteries and 'backup' batteries, but rather primary batteries are disposable batteries and secondary batteries are rechargeable.

In primary batteries, the chemical energy stored in the cells of the battery "is irreversibly converted into electrical power" when an electric current is supplied (Ball et al. 2007). Secondary batteries provide power in the same way, but electric current must be passed through them initially to incite a chemical change in the material of the cell before it can be used to generate electrical power (Carhart 1891). Once the material in the secondary battery has been modified by the flow of electric current, meaning the rechargeable battery has been charged, it will retain that chemical energy. Then, when an electric current is applied to the charged secondary battery, the stored chemical energy will be converted into electrical power, just as in the primary battery. After the secondary battery has exhausted its supply of stored chemical energy, electric current can be applied again to modify the material so that it stores chemical energy. In summary, primary batteries contain "a store of potential energy in the materials which admit of chemical reactions," while secondary batteries are "only a reservoir, capable of storing energy by means of the chemical changes produced by electrolysis" (Carhart 1891).

The drawback of using secondary batteries on spacecraft with a long cruise time before the mission is that secondary batteries do not store their charge for long durations. The four Pioneer Venus probes used AgZn (Silver-Zinc) secondary batteries, but they had to be charged on the launch pad just before leaving Earth to ensure they would still have enough stored energy for the mission after a 4 month cruise to Venus.

Primary batteries store for several years, but their performance depends on their temperature during storage and while in use. Storing them at low temperatures minimizes the amount of discharge that occurs (discharge “can increase by as much as 20% for a 5 K increase in temperature”), while operating the batteries at moderate temperatures improves their capacity (“perhaps by 10% for a 10 K increase in temperature”) (Ball et al. 2007). The Galileo probe was powered by $LiSO_2$ primary batteries, which were required to travel through space for more than six years before performing the mission (Dagarin et al. 1996).

8.2. Radioisotope Thermoelectric Generators (RTGs)

An RTG acts as a generator by converting the heat produced during the radioactive decay of a radioisotope into electrical power. The most common radioisotope used is ^{238}Pu. RTGs are a fairly reliable power source and last for extremely long periods of time. They have a higher energy density than batteries, meaning the are able to supply more Watt-hrs per kilogram. The very long lasting Viking Landers were each powered by two ^{238}Pu RTGs.

Unlike batteries, RTG performance does not depend greatly on the temperature of the environment. Currently, RTGs are the only flight tested form of long duration power in the outer Solar System, where solar radiation is very low.

The major draw back of RTGs is the extreme cost associated with them. Because they contain radioactive material, safety becomes an over-ridding concern and lots of money must be spent to deal with all of the safety regulations. It is often thought that the level of concern is far too high and that the likelihood of something happening is extremely low.

8.3. Solar Arrays

Solar arrays, as previously mentioned, are a means of providing power for a higher energy requirement mission. They are used in conjunction with secondary batteries. The solar arrays collect solar energy and create electric current, which flows through the secondary batteries and charges them. The lander can then use the chemical energy stored in the batteries to create electrical power, even when the sun is not shining. Currently, the highest efficiency solar panels contain GaAs (Gallium Arsenide) multi-junction solar cells. Multi-junction cells are multiple layers, placed one on top of the other, and each layer matches a different wavelength band of the solar spectrum. As the light passes through the multi-junction solar panel, more parts of the solar spectrum are captured and converted into electricity than if the panel were only one layer. However, the more efficient GaAs multi-junction arrays are still only about 25-30% efficient. The solar panels on the Phoenix Lander are GaAs multi-junction arrays.

Another downside is that solar arrays only work as an energy source in locations that receive enough direct solar radiation. The sun is not always above the horizon and, even if it is, the solar panels are not always oriented in a direction that receives acceptable sun light.

9. Discussion

Human kind has successfully sent landers to seven objects in the Solar System (including the Moon). Considering the number of planets, moons, minor planets (with known orbits), Kuiper Belt Objects, and comets in the Solar System, the fact that humans have *in situ* observations from only eight of these objects (including Earth) is daunting. Using the object totals for these Solar System bodies from December 2008 and January 2009, there are 589,473 total known objects in the Solar System. Humans have direct observations from 0.0014% of the objects in the Solar System. If the Philae Lander is successful and transmits data from the surface of the comet 67P/Churyumov-Gerasimenko, then the percentage will increase to 0.0015%. Human kind has quite a bit of exploring to do before truly knowing what is contained in the Solar System.

Landers are an important tool for Solar System exploration. They represent an intermediate stage between orbiters and rovers, and a step towards human exploration. Not only are landers a productive means of obtaining *in situ* observations, but they are less complex than rovers, often making them a less expensive option for similar types of observations. Landers lack the mobility of rovers, but if sent to the correct location, the data from landers can be just as valuable.

REFERENCES

Abelson, R. D., & Shirley, J. H. 2005, Space Technology and Applications International Forum - STAIF 2005, 746, 303

Anderson, D. L., et al. 1976, Science, 194, 1318

Arvidson, R. E., Gooding, J. L., & Moore, H. J. 1989, Reviews of Geophysics, 27, 39

Ball, A. J., Garry, J. R. C., Lorenz, R. D., & Kerzhanovich, V. V. 2007, *Planetary Landers and Entry Probes*. New York: Cambridge University Press.

Basilevsky, A. T., Ivanov, M. A., Head, J. W., Aittola, M., & Raitala, J. 2007, Planet. Space Sci., 55, 2097

Bienstock, B. J. 2004, Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, 544, 37

Carhart, H. S. 1891, *Primary Batteries*. Boston: Allyn and Bacon.

Dagarin, B. P., Taenaka, R. K., & Stofel, E. J. 1996, Aerospace and Electronic Systems Magazine, IEEE, 11, 6, 6-3

de Pater, I. & Lissauer, J. J. 2001, *Planetary Sciences*. New York: Cambridge University Press.

Dunham, D. W., et al. 2002, Icarus, 159, 433

Garcia, M. D., Fujii, K. K. 2007, AAS 07-247

Larmat, C., Montagner, J.-P., Capdeville, Y., Banerdt, W. B., Lognonné, P., & Vilotte, J.-P. 2008, Icarus, 196, 78

Lebreton, J.-P., et al. 2005, Nature, 438, 758

Lebreton, J.-P., & Matson, D. L. 2002, Space Science Reviews, 104, 59

Linkin, V., et al. 1998, Planet. Space Sci., 46, 717

Lognonné, P., et al. 1998, Planet. Space Sci., 46, 739

Marcoux, L. S., & Dagarin, B. P. 1983, NASA. Goddard Space Flight Center The 1982 Goddard Space Flight Center Battery Workshop p 15-22 (SEE N83-35230 23-33), 15

Matson, D. L., Spilker, L. J., & Lebreton, J.-P. 2002, Space Science Reviews, 104, 1

Mutch, T. A., Binder, A. B., Huck, F. O., Levinthal, E. C., Morris, E. C., Sagan, C., & Young, A. T. 1972, Icarus, 16, 9

Mutch, T. A., et al. 1976, Science, 194, 1277

NASA Science Missions: Mars 2016 (http://nasascience.nasa.gov/missions/mars-2016). Accessed April 2009.

National Space Science Data Center: Lunar and Planetary Science. Spacecraft Query (http://nssdc.gsfc.nasa.gov/nmc/SpacecraftQuery.jsp). Accessed April 2009.

Richter, L., Coste, P., Gromov, V., Kochan, H., Pinna, S., & Richter, H.-E. 2001, Advances in Space Research, 28, 1225

Smith, P. H., et al. 1997, J. Geophys. Res., 102, 4003

Soffen, G. A., & Young, A. T. 1972, Icarus, 16, 1

Titov, D. V., et al. 2002, Earth-like Planets and Moons, 514, 13

Yano, H., et al. 2006, Science, 312, 1350

Fig. 1.— Plot showing lander destinations as a function of launch date. The countries that contributed the primary amount of funding for the lander mission are indicated by the shape of the data point and the name of the mission labels each data points. For missions launched together or in close proximity, the overlapping data points are given one combined label.

Fig. 2.— Diagram indicating which power methods are best for a given duration mission and power requirement. Figure taken from Ball et al. (2007).

Table 1. Where have we been with landers?

Solar System Object	Lander	Funding	Launch Date	Landing[a] Date	Planned Duration	Actual[b] Duration
Venus	Venera 7	USSR	Aug 1970	Dec 1970	?	d:35min, s:23min
	Venera 8	USSR	Mar 1972	Jul 1972	?	d:55min, s:50min
	Venera 9	USSR	Jun 1975	Oct 1975	?	53 min
	Venera 10	USSR	Jun 1975	Oct 1975	?	65 min
	Pioneer Large	USA	Aug 1978	Dec 1978	?	d: 54 min[f]
	Pioneer Sm North	USA	Aug 1978	Dec 1978	?	d: 53 min[f]
	Pioneer Sm Day	USA	Aug 1978	Dec 1978	?	d:56min, s:67min
	Pioneer Sm Night	USA	Aug 1978	Dec 1978	?	d:56min, s:2sec[g]
	Venera 11	USSR	Sep 1978	Dec 1978	?	95 min
	Venera 12	USSR	Sep 1978	Dec 1978	?	110 min
	Venera 13	USSR	Oct 1981	Mar 1982	?	127 min
	Venera 14	USSR	Nov 1981	Mar 1982	?	57min
	Vega 1	USSR	Dec 1984	Jun 1985	?	20 min
	Vega 2	USSR	Dec 1984	Jun 1985	?	?
Mars	Mars 3	USSR	May 1971	Dec 1971	?	20 sec
	Viking 1	USA	Aug 1975	July 1976	90 days	6 yr, 5 mos[d]
	Viking 2	USA	Sep 1975	Sep 1976	90 days	3 yr, 3 mos[d]
	Mars Pathfinder	USA	Apr 1996	Apr 1997	?	2 mos, 23 days
	Mars 96	Russia	Nov 1996	n/a[c]	1 yr	0 sec
	Mars Polar Lander	USA	Jan 1999	(Dec 1999)	∼3 mos	0 sec
	Beagle 2	UK	Jun 2003	(Dec 2003)	180 days	0 sec
	Phoenix	USA	Aug 2007	May 2008	3 mos	5 mos
Phobos	Phobos 2	Russia	July 1988	(Mar 1989)	$\geq$3 mos	0 sec
Asteroid: Eros	NEAR-Shoemaker	USA	Feb 1996	Feb 2001	0 sec[f]	14 days
Asteroid: Itokawa	Hayabusa	Japan	May 2003	Nov 2005	?	?
Jupiter	Galileo	USA	Oct 1989	Dec 1995	?	61 min
Titan	Huygens	ESA	Oct 1997	Jan 2005	d: 150 min	d:149.5min, s:70min
Comet: 67P	Philae Lander	Europe	Mar 2004	Nov 2014[h]	∼3 mos	-

[a]Parenthesis indicate unsuccessful landings

[b]'d:' is descent duration, 's:' is surface duration. If not labeled, the time is surface duration (meaning data was not taken during the descent).

[c]Mars 96 never left Earth due to the failure the 2^nd burn of the 4^th stage of the rocket, so a landing on Mars was not possible.

[d]Viking 1 Lander lasted 2252 sols, Viking 2 Lander lasted 1215 sols. (Arvidson et al. 1989)

[e]The NEAR-Shoemaker spacecraft was designed as an orbiter and never planned to land.

[f]Mission ended with probe impacted the surface of Venus.

[g]Bienstock (2004) claims Night Small Probe did not operate on the surface, but Ball et al. (2007) says it operated for 2 seconds after impacting the surface.

[h]Planned landing date.

Table 2. Lander Stats

Lander	Year	Lander Type	Entry Mass (kg)	Landed Mass (kg)	Size (m)	Power Supply	Power (W)	# Instr	Instr[a] Power (W)
Venera 7	1970	atmos	500	?	1	pri. bat.	?	?	?
Mars 3	1971	pod	1210	350	?	pri. bat.	?	?	?
Venera 8	1972	atmos	495	?	1	pri. bat.	?	?	?
Venera 9 & 10	1975	legged	1560	660	?	bat.	?	?	?
Viking 1 & 2	1975	legged	1185	612	?	2 ^{238}Pu RTGs, NiCd sec. bat.	90	11	?
Pioneer Large	1978	atmos	302	193	0.78[e]	AgZn sec. bat.	?	7	106
Pioneer Small	1978	atmos	94	61	0.47[e]	AgZn sec. bat.	?	3	10
Venera 11 & 12	1978	legged	∼1700	∼760	?	bat.	?	?	?
Venera 13 & 14	1981	legged	∼1700	760	?	bat.	?	?	?
Vega 1 & 2	1984	legged	1750	∼750	?	bat.	?	?	?
Phobos 2	1988	sm-bod	?	67	?	solar arrays, sec. bat.	?	6	?
Galileo	1989	atmos	339	-	1.26	$LiSO_2$ pri. bat.	?	7	20
NEAR-Shoemaker	1996	sm-bod	487	487	1.7	4 solar panels	1,800	?	?
Mars Pathfinder	1996	pod	585.3	264[c]	?	solar panels, AgZn sec. bat.	∼177	5	?
Mars 96	1996	pod	87	33	?	2 ^{238}Pu RTGs, NiCd sec. bat.	.44	7	?
Huygens	1997	atmos	318	∼200[b]	?	$LiSO_2$ pri. bat.	?	6	?
Mars Polar Lander	1999	legged	583	290	3.6x1.06	GaAs solar panels, NiH sec. bat.	200	?	?
Hayabusa	2003	sm-bod	510	510	1x1.6x2	solar panels?	?	9	?
Beagle 2	2003	pod	68.84	33.2	0.65x0.25	GaAs solar panels, Li-ion sec. sat.	?	6	?
Philae	2004	sm-bod	97.4	97.4	?	solar array, Li-ion sec. bat.[d]	100[d]	10	?
Phoenix	2007	legged	350	328	1.5	GaAs solar panels, sec. bat.	?	5	?

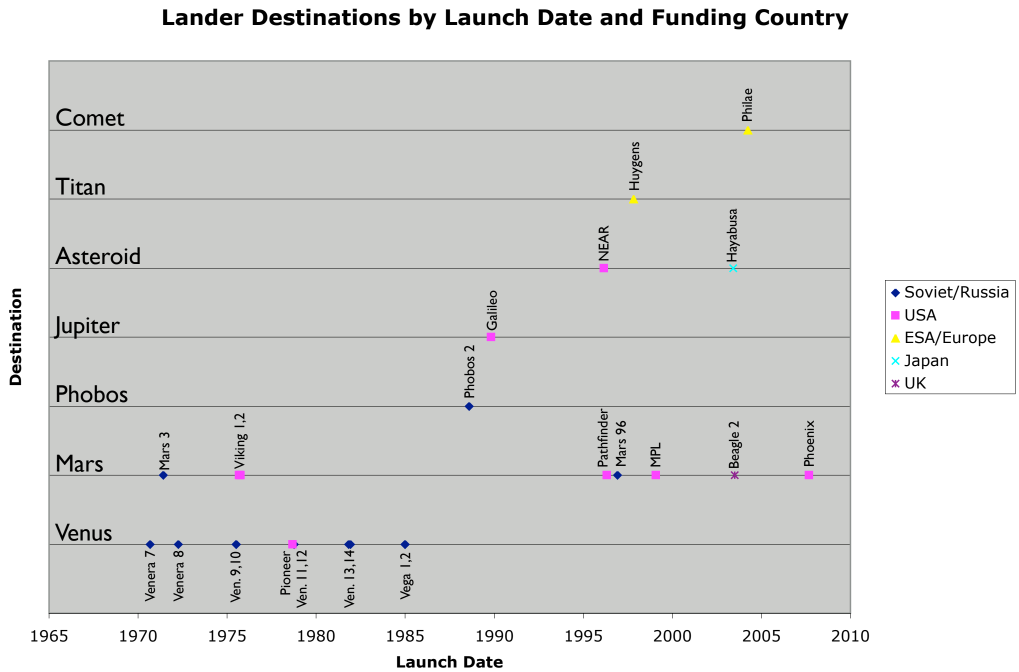
[a]The amount of power required by instruments

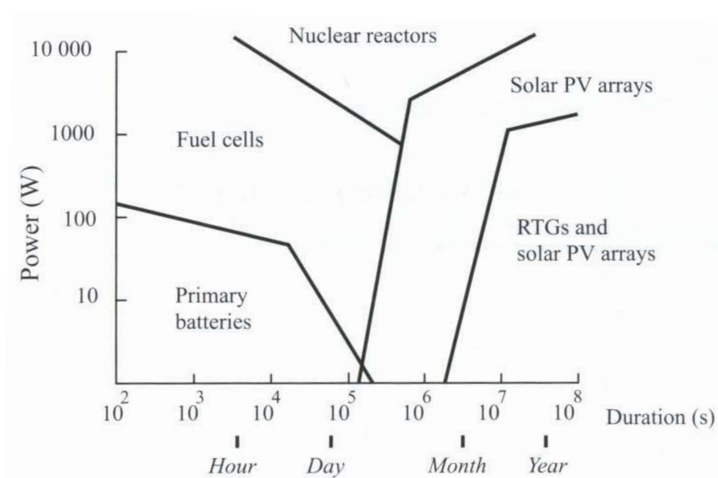
[b]"∼200 kg without entry and descent subsystems" (Ball et al. 2007)

[c]"Landed mass 410 kg (incl. 99 kg airbag system, 264 kg lander + 10.5 kg rover)" (Ball et al. 2007)

[d]These values are for the long-term mission. The first 5 days of the mission the power supply is a $LiSOCl_2$ primary battery, providing ∼1 kWh (Ball et al. 2007)

[e]Diameter of Pressure Vessel. Aeroshell diameter is 1.42 m (large probe) and .76 m (small probe)


Lander Destinations by Launch Date and Funding Country
Destination
Comet
Titan
Asteroid
Jupiter
Phobos
Mars
Venus
Philae
Huygens
NEAR
Hayabusa
Galileo
Phobos 2
Mars 3
Viking 1,2
Pathfinder
Mars 96
MPL
Beagle 2
Phoenix
Venera 7
Venera 8
Ven. 9,10
Pioneer
Ven. 11,12
Ven. 13,14
Vega 1,2
Soviet/Russia
USA
ESA/Europe
Japan
UK
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Launch Date


Power (W)
10 000
1000
100
10
Nuclear reactors
Solar PV arrays
Fuel cells
RTGs and
solar PV arrays
Primary
batteries
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Duration (s)
Hour
Day
Month
Year