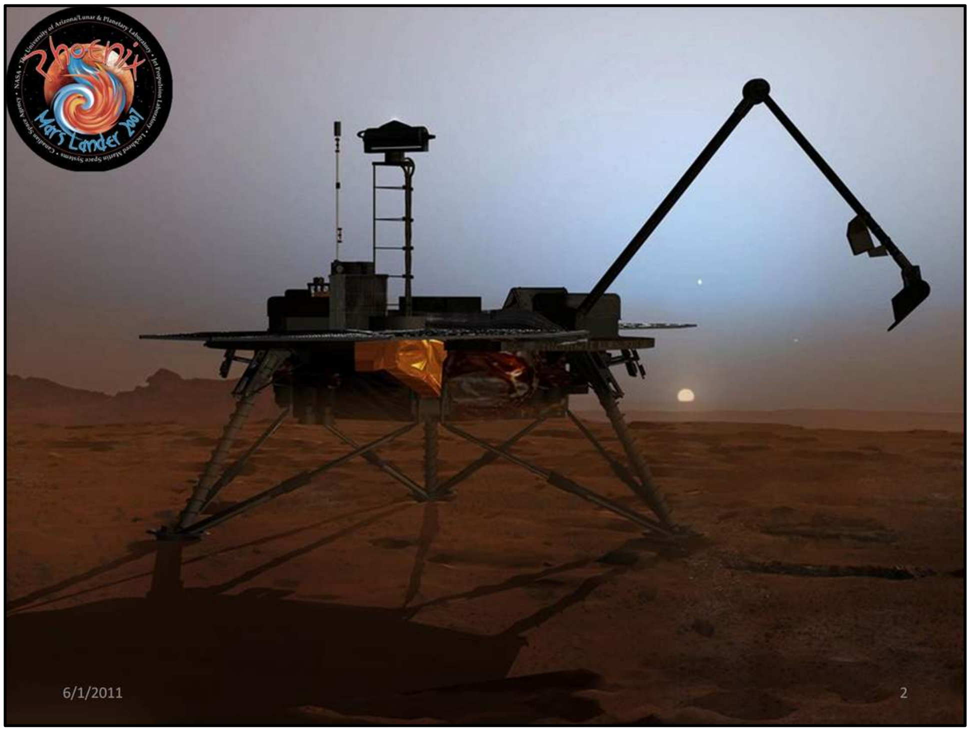
Slide 1: Intro Page

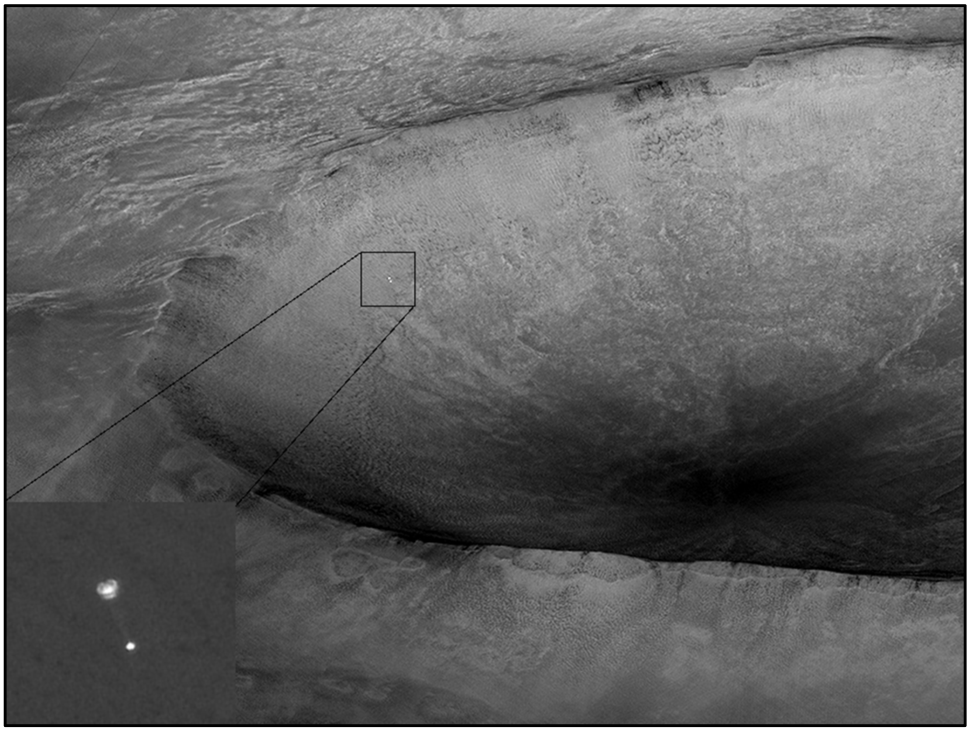
For many NASA missions, power efficiency is not a critical factor, and doesn't get much attention. However, attention to power efficiency could have an enabling role in some exciting future missions, and could be very important to NASA and solar system science. Understanding why efficiency is often ignored, despite its importance, requires some context, which I'll try to give you by discussing how efficiency effects a few of the very current missions, and how it might enable some possible future missions.

In many circumstances where an engineer is working on a project, the primary goal is to meet requirements within available resources. Stripped to its essentials, this is one way to look at NASA's methodology for funding missions: Develop a set of science goals (level 1 requirements) (sometimes as loose as "do good science") and provide a strict dollar cost cap within which those goals must be met. If it is a competed missions, ideas are brainstormed, proposal teams are formed, and mission concepts are developed. At JPL and elsewhere the proposal teams start looking at spacecraft and instrument technologies – with a weather eye always on the cost – to develop a mission that will fit within the cost cap. For low cost cap competed missions – for example, the Mars Scout, Discovery, or even New Frontiers programs – this has often meant "use heritage": possibly re-flight of an existing design with build-to-print hardware, or even scrounging spare hardware from a previous mission.



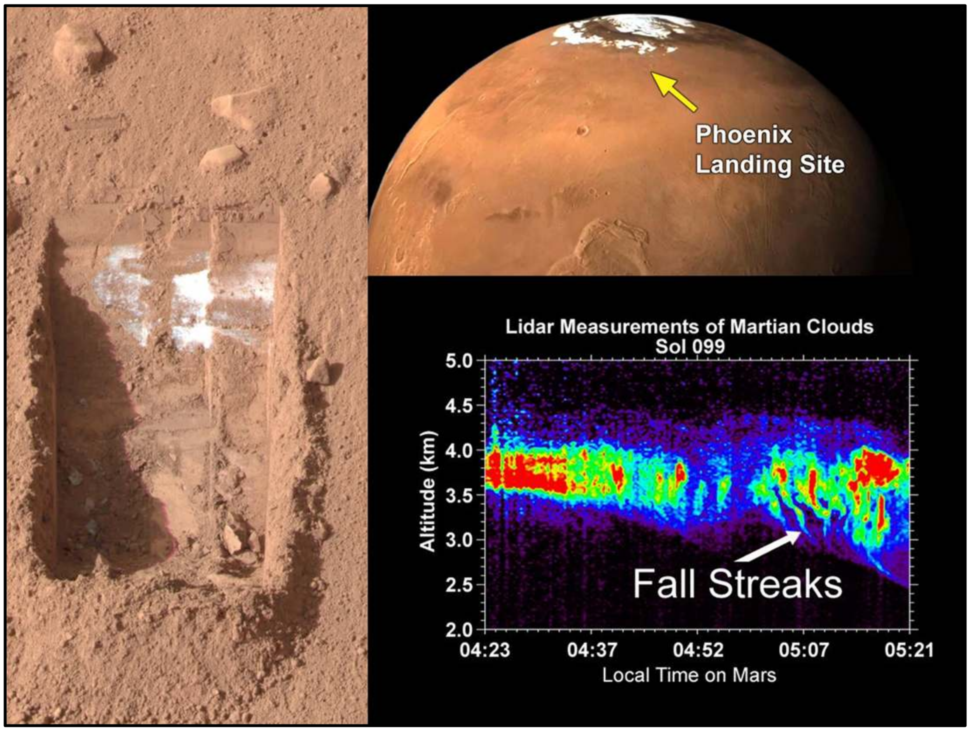
Slide 2: Phoenix image

A prime example of the latter is the Phoenix Mars Scout Mission, developed starting from existing hardware and instruments from the cancelled Mars 2001 mission, and named because it rose from the ashes of Mars 2001. The goal in this case is to use existing hardware and technology, and make the minimum possible accommodations for compatibility with the new mission requirements. This usually works well at the proposal stage but can be frustrating when you actually have to build the thing! But the cost cap is critical: For a NASA mission, the important figure of merit is science return for mission cost. So permit me to generalize the notion of efficiency as the ratio of the desired output to the required input. For space missions I will call this figure of merit the "*mission efficiency*." I can't give you a numerical conversion factor, but in the famous words of a past supreme court justice, "I know it when I see it."



Slide 3: Image of Phoenix on chute from HiRise

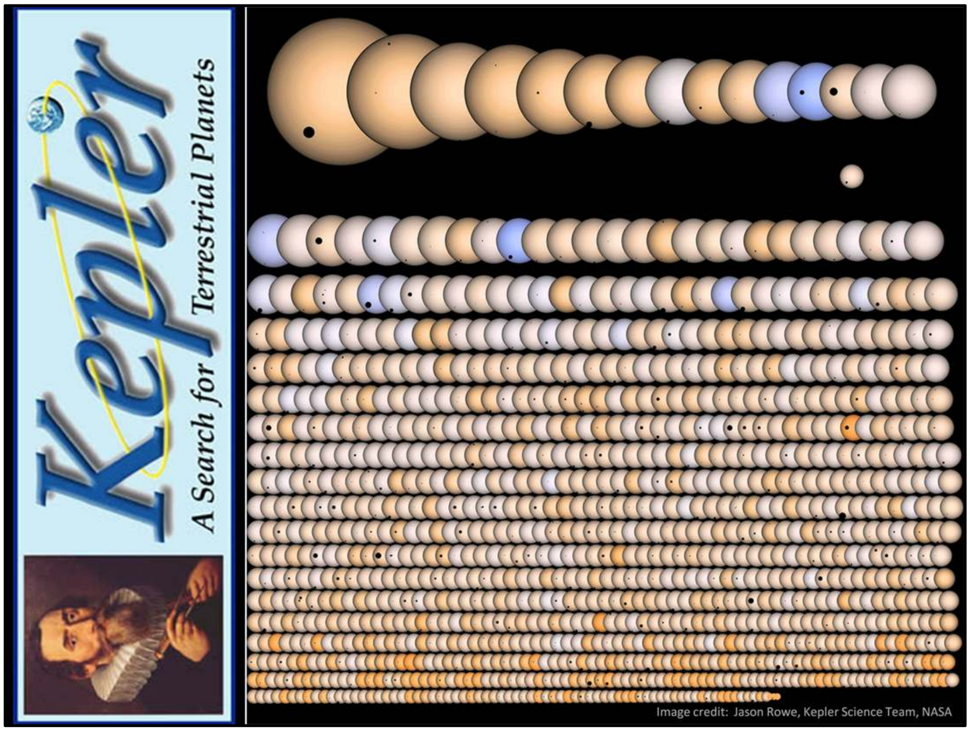
NASA's methodology is successful – I would even call it efficient. It did result in the Phoenix mission that on a very small Mars Scout budget, landed a spacecraft in the polar regions of Mars: A very difficult feat at any budget! By the way, this picture, taken from the Mars Reconnaissance Orbiter from Mars orbit, is of Phoenix descending to Mars on its parachute. How cool is that?



Slide 4: Phoenix image of ice in the trench and Lidar data

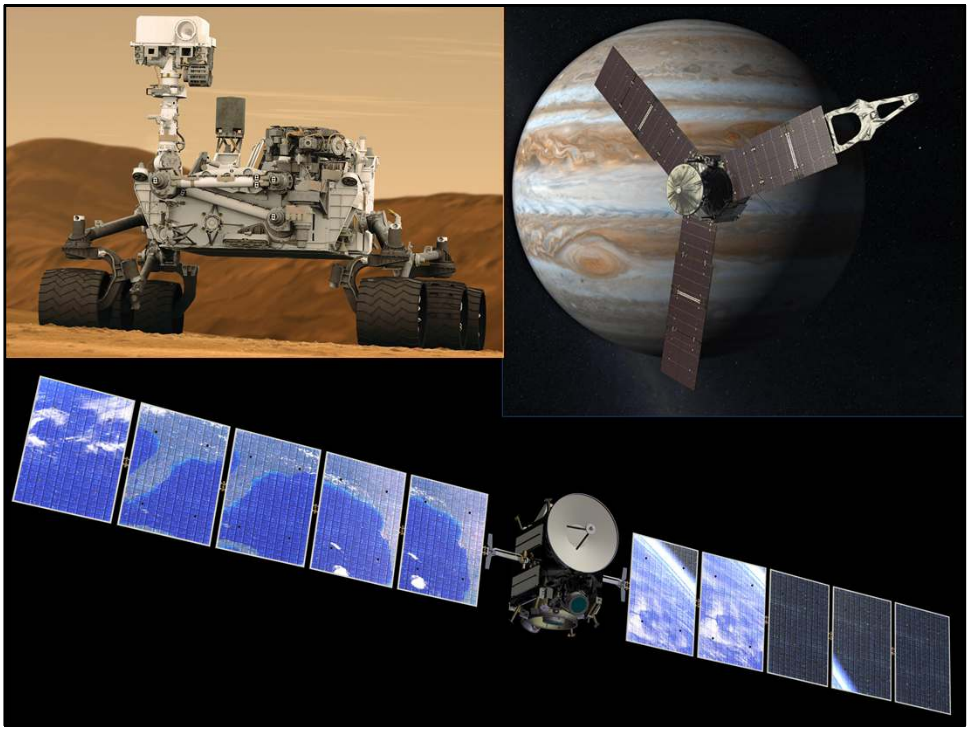
Phoenix made many important discoveries, for example, not just ***evidence*** of water on Mars, but water ice was found under the soil very near to the surface; and it actually detected snow falling! Snow was seen in measurements by the LIDAR instrument, as you can see by the fall streaks in the plot, but also seen in videos as it fell through the LIDAR laser.

Slide 5:Kepler mission image
NASA's mission development methodology has also given us the Kepler Discovery mission, out there looking for exo-planets, and shown here having spotted one. For *mission efficiency*, Kepler has to be one the best things going: It has found **16** confirmed planets to date and…

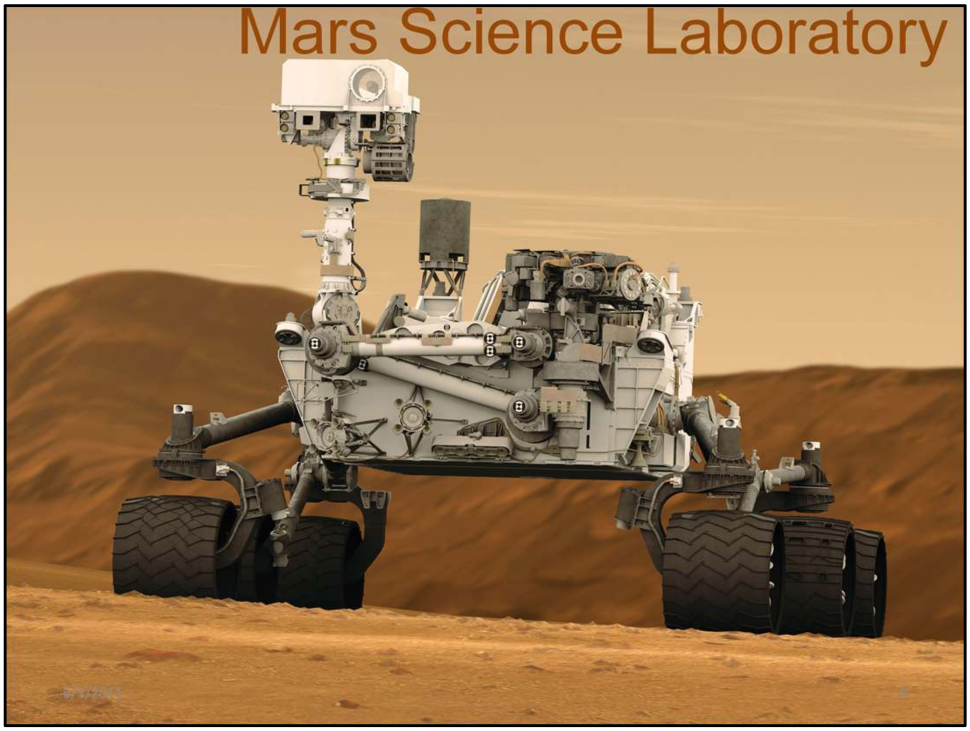


Slide 6: Image of Kepler stars/planets
Recently the Kepler project released the news that they have found **1235** candidates for planets – okay, they exist only as transit data as yet, not yet confirmed by additional observations, but still: Many of them will be confirmed. In this slide these potential star systems are shown to scale as planets silhouetted against their suns. This could be the most efficient use of mission resources ever: Give them a Discovery mission budget and get back 1251 planets! And they're not done yet.

These missions and many others using this paradigm have succeeded in giving us many fantastic discoveries. For these missions that I've mentioned, power efficiency was not a critical driver, as they are very well matched to accomplishing exactly their science requirements without much concern about power efficiency, achieving high (or at least sufficient) *mission efficiency*. There are also other missions which have been fit (or at least tried to fit) into the same paradigm, but that could have benefited if power efficiency had been recognized as a driver of *mission efficiency* from the beginning. There are additional missions that may be achievable with current technology but which certainly cannot be without greatly improving power efficiency. Neither of these change the paradigm – they just add a requirement that may not be regarded as strictly necessary in all cases, particularly for engineers trying to deliver components to ATLO on time.



Slide 7: Montage of MSL Rover Image, Juno at Jupiter image, Dawn image
I will discuss three missions for which power efficiency was not a primary concern, but if it had been it would have improved the *mission efficiency*: the Mars Science Laboratory (MSL) (shown here in the upper left) scheduled to launch next November, the Juno New Frontiers Mission to Jupiter (upper right) launching in August, and the Dawn Discovery Mission to the asteroids Vesta and Ceres, currently on approach to enter orbit around Vesta in July.

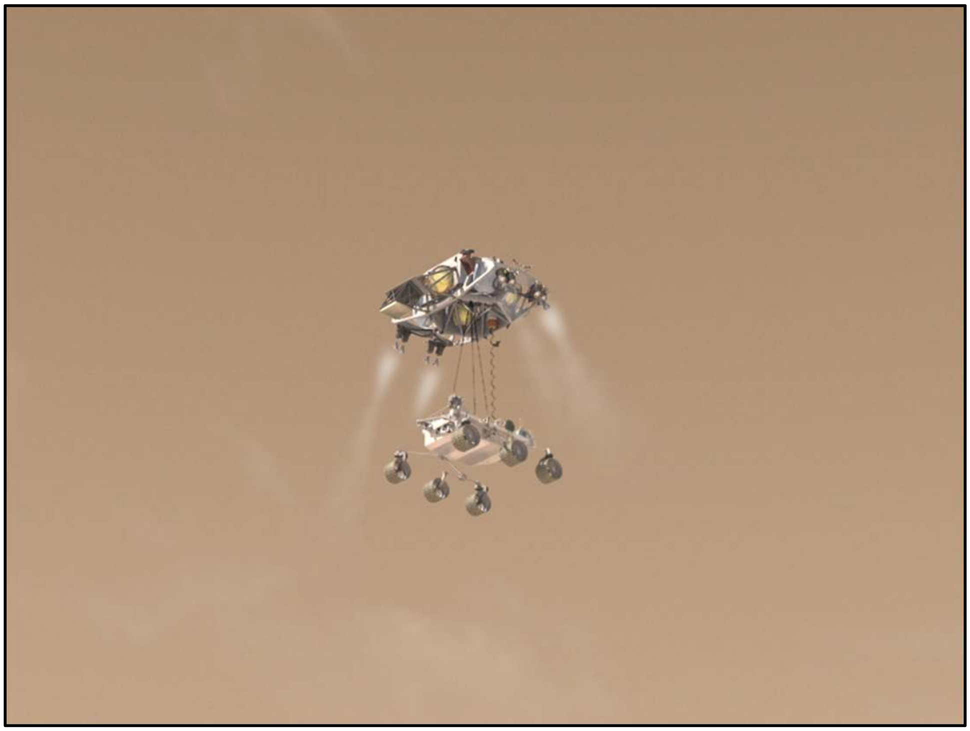


Slide 9: MSL Rover on Mars / click to fade in to Comparison image of the three rovers

The Mars Science Laboratory is a Mars rover, like the Pathfinder and MER rovers, shown here for comparison: MSL is the big one. As you can see, it takes the concept to a new level

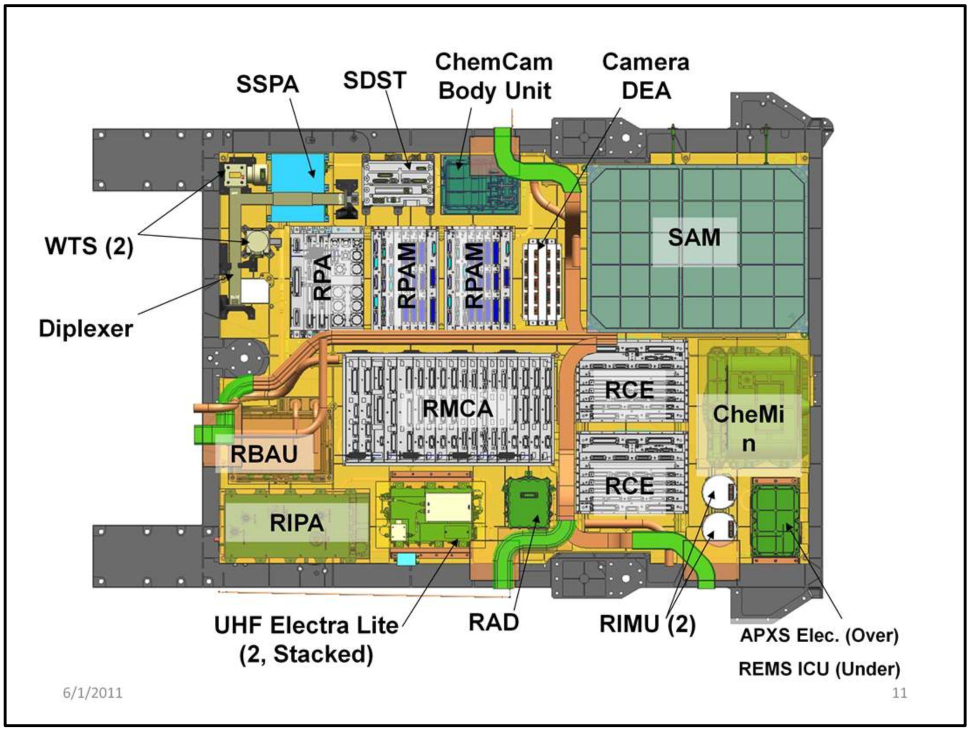
Slide 9: MSL Rover on Mars / click to fade in Mini / click to transparent mini / click to fly away

The MSL rover is the size of a small car and masses 930kg: This is compared to 1215 kg for the Mini-Cooper (shown here approximately to scale.)



Slide 10: Rover descent

Entire new mission technologies have been invented to place this large rover on Mars, including the new skycrane landing system, which you see here on its way to deposit the rover on the surface. MSL carries 10 instruments to accomplish its mission of acquiring scientific data about the region in which it lands, conducting mobile in situ analysis, selecting, acquiring, processing, distributing, and analyzing rock samples, all while driving for 20km during 600 martian days. But – and this is where it gets interesting from the efficiency standpoint – it has to do all this with about 100W of electrical power from a single radioisotope thermal generator! While it does have the thermal advantage of a couple of kilowatts of waste heat from the RTG to keep itself warm, it still needs to drive around while using about the same average power as an incandescent light bulb. This is accomplished by duty cycle: Put everything possible into low power mode while slowly charging batteries that have enough capacity to actually drive the motors or to operate the sampling system and science instruments. IThe MSL design is a brilliant engineering and scientific achievement (or it will be once we get it safely to Mars) but it was *not* built or designed with power efficiency in mind.

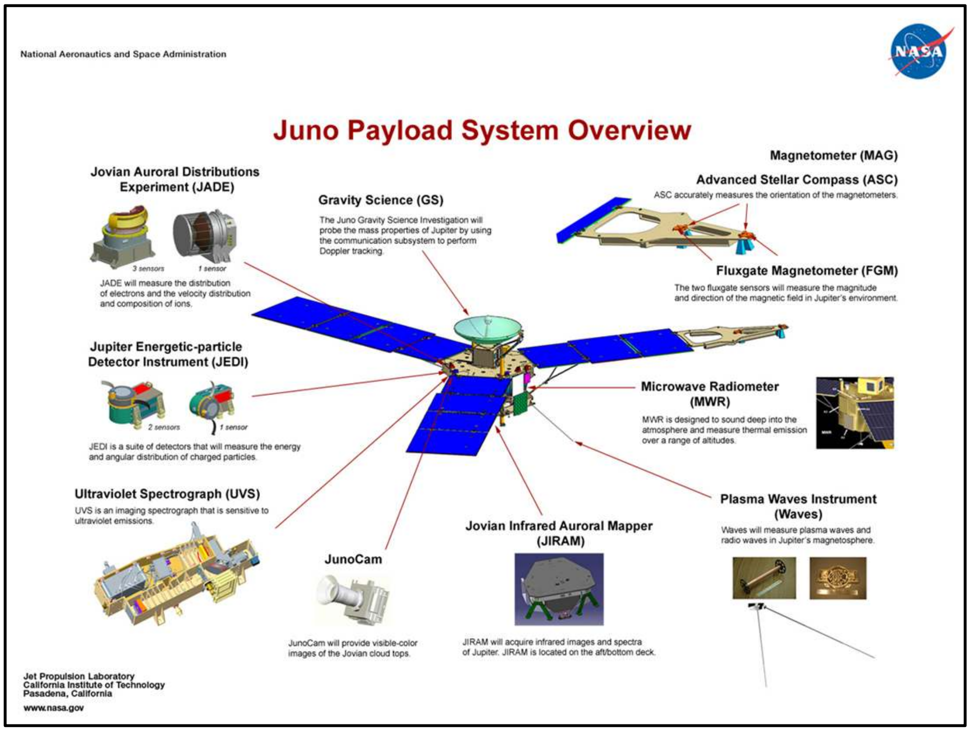


Slide 11: Picture of MSL rover interior

This slide illustrates how many electronic subsystems there are just in the chassis, (there are many others mounted on the outside of the chassis, on the robotic arm and on the mast.) Some of the rover electronics, which aren't all that low power to begin with, are operating at 35% efficiency power delivered to the load, and even at this late date, methods are being explored to improve the overall power efficiency. This is a case where every Watt of additional power that can be made available translates directly into more science and a longer traverse: which is, again, greater *mission efficiency*.

Slide 12: Image of Juno at Jupiter

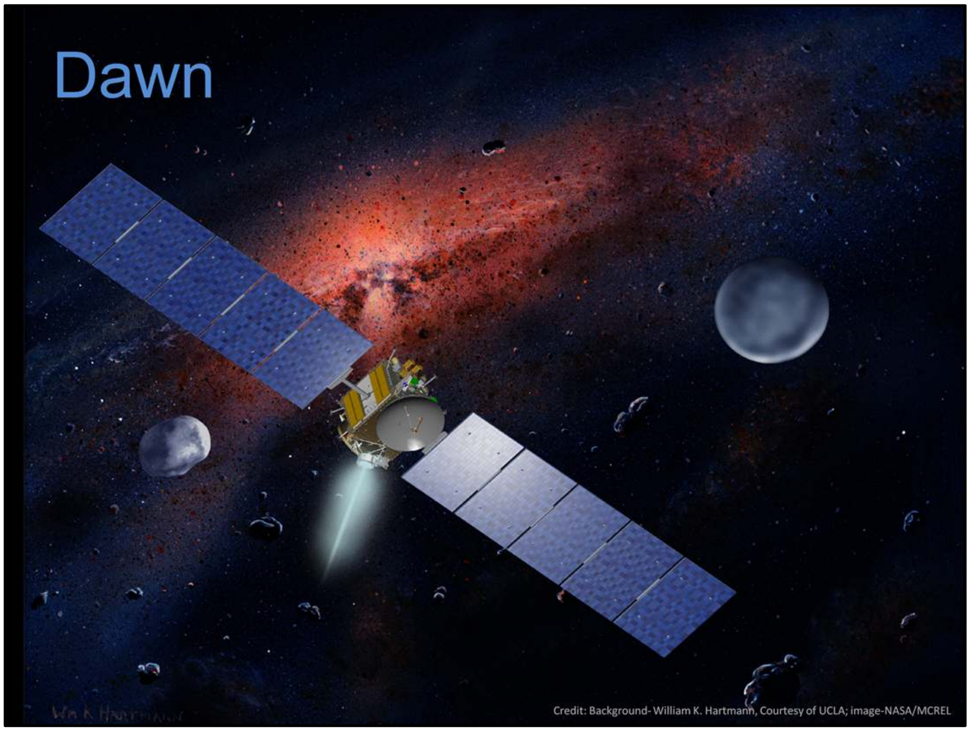
The Juno mission is not only exciting for the science goals, but for a power guy like me, it's exciting because it is the first solar powered mission to Jupiter. It will operate entirely on solar power at a distance five times farther than the distance from the sun to the Earth, investigating Jupiter's origins, interior structure, magnetosphere, and that amazing atmosphere, and doing it from a weird elliptical orbit designed to minimize the exposure of the spacecraft to the high radiation around Jupiter.



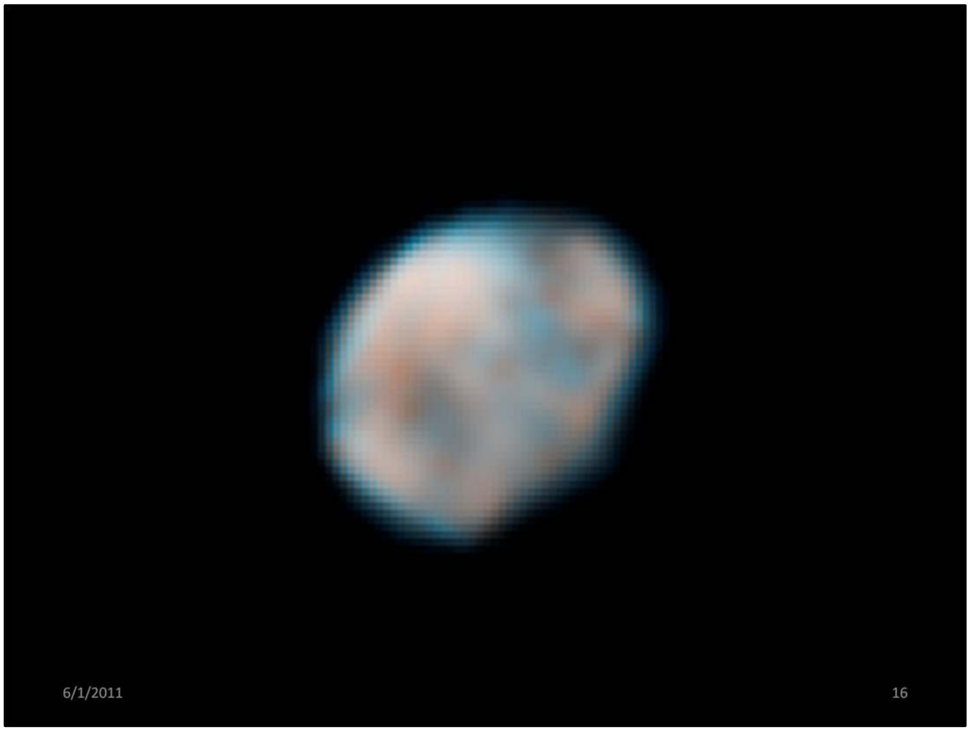
Slide 13: Juno instruments poster

It carries eight science instruments, including a student experiment called JunoCam that will take the first images (ever) of Jupiter's polar regions.

Slide 14: Juno Array Image
I don’t have time to through them all, but eight’s quite a few instruments! To accomplish all this science, it carries a very large solar array, more than 60 square meters in three panels, constructed from slightly fewer than 19000 solar cells painstakingly screened for optimal response to the conditions at Jupiter.   All so that it can have total end of life power of 410W, with between 55—90W of that power available for operating science instruments. If the metric were: power given to science, compared to the total power budget, Juno is 13—22% efficient. This is a pretty good for a spacecraft, but still a good example in which a more efficient spacecraft could have been traded for a smaller solar array to accomplish the same science (and incidentally save on the cost of manufacturing and screening more than19000 solar cells as well) or alternatively, for more power to do more science. Juno has a great project team that has done a great job at meeting its requirements within its cost constraints, but *mission efficiency* could have been significantly improved with more efficient utilization of those giant solar arrays.

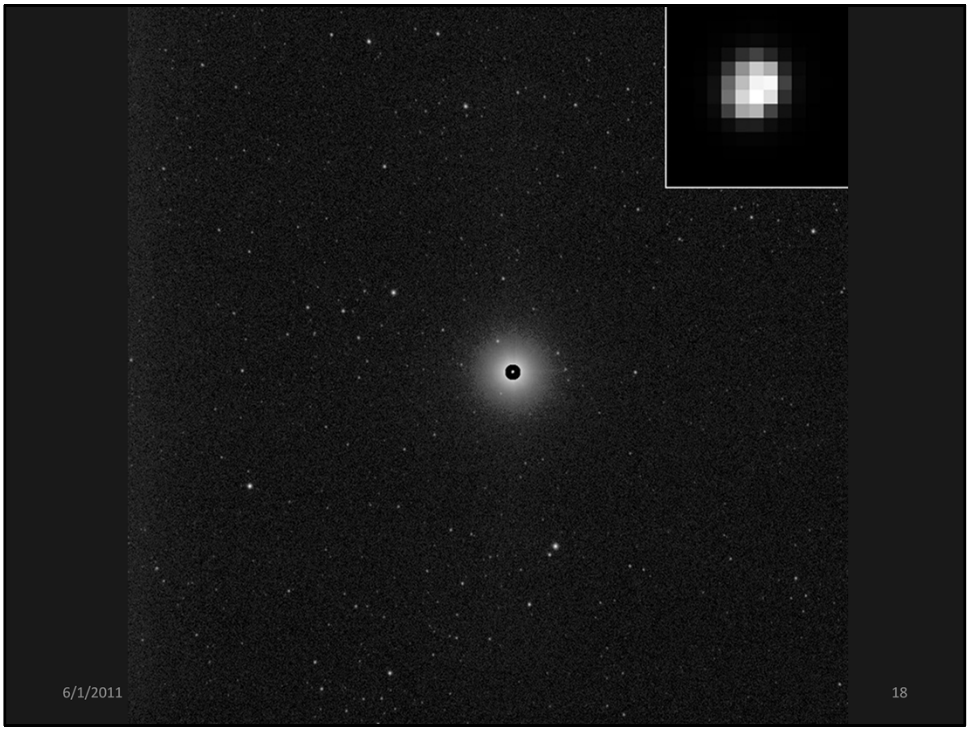


Slide 15: Dawn Image with Ceres/Vesta
The Dawn Mission is a solar powered ion propulsion mission on its way to visit the two largest objects in the asteroid belt,



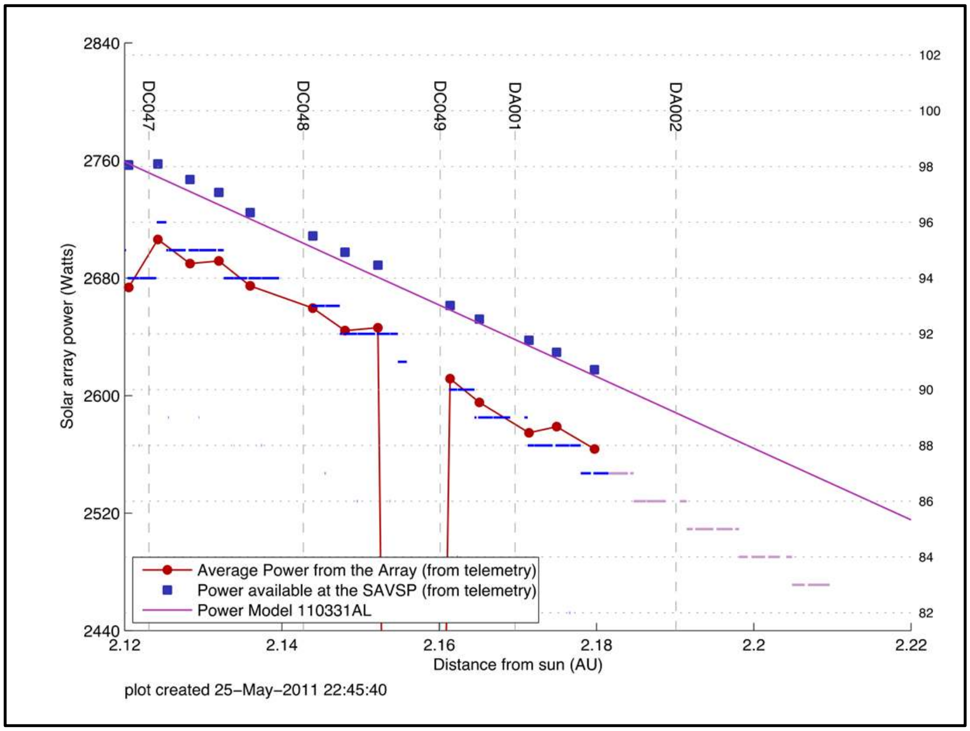
Slide 16: Image of Vesta
First to Vesta, shown here in an image taken by the Hubble space telescope. As of today, the spacecraft is about 450,000km from Vesta

Slide 18: Image of Ceres
And second to Ceres, which is so large that it is classified as a dwarf planet, like Pluto.



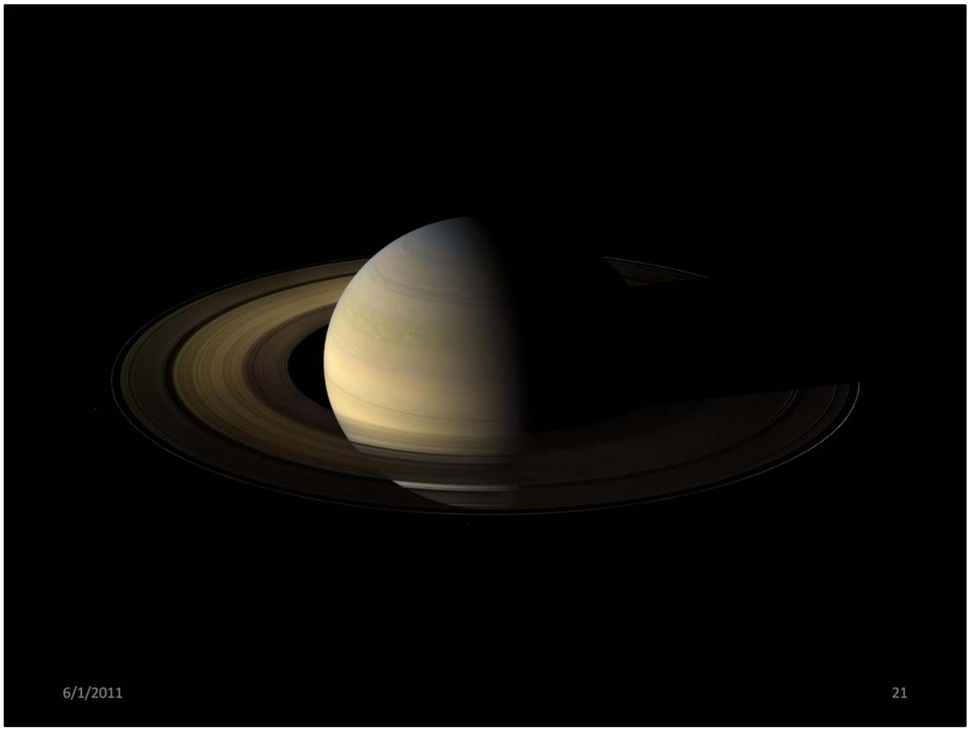
Slide 19: First image of Vesta
Dawn will investigate Vesta and Ceres using a visible and infrared spectrometer, a gamma ray and neutron spectrometer, the spacecraft itself (and the Deep Space Network) to study the detailed gravitational structure of the asteroids, and of course, a camera. What is shown here is the first image of Vesta obtained by the mission, just four weeks ago. You may not see the improvement over the Hubble image, but the year is young! Along with Kepler, Dawn is also one of the next most efficient uses of mission resources going. Most spacecraft (including MSL and Juno) only visit one planet, but Dawn won't stop there: Dawn will be the first unmanned spacecraft to visit one planet, then leave that planet (okay, large asteroid) and go visit another planet (okay, it's a dwarf planet: just like Pluto)

Slide 20: Image of Dawn Launch
Launched in 2007 from a facility that is not very far from where we are tonight, it's eight year mission, to explore new worlds, to boldly go where no mission has spacecraft has gone before, and take really cool pictures! It already has the record for total Delta-V, currently at 6.54 km/sec since launch (as of today) exceeding the previous record set by DS1 at 4.3 km/sec, and Dawn has much more Delta-V to go before it's done. Using solar electric propulsion and its 36 square meter solar arrays, it will eventually get out to 2.84AU.



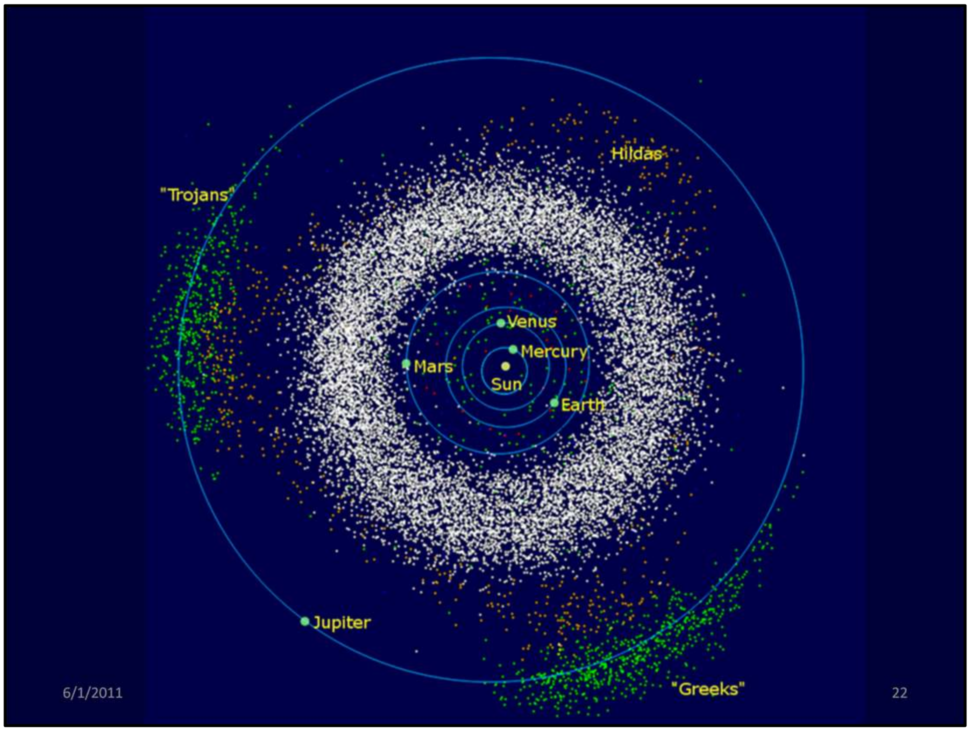
Slide 21: Dawn Power Summary Chart
But I speak from authority as the power system engineer on the Dawn spacecraft team that the Dawn mission would have benefited greatly from higher power efficiency. This plot shows a summary of the Dawn power for the last few months, and you can see the inexorable decrease in the available solar array power, which is shown by the blue squares.

The solar array started out at 1AU at about 10kW, but is currently operating at around 2.6kW, and will be down to less than half that when it gets to Ceres. Now this seems like quite a bit of power (compare it to Juno or MSL) until you realize that during thrusting with the ion propulsion system, and while the spacecraft is not communicating with Earth (i.e., the telecom system is off) the spacecraft still requires about 520W average power to operate the flight system, more than Juno at the beginning of its mission at Jupiter. As of last summer, the spacecraft has had to operate at less than maximum thrust in order to have sufficient power for the flight system. In Dawn's case, higher efficiency would have translated directly into greater *mission efficiency* (all else being equal) by providing more power for thrusting. This would have led to a faster transit time to Vesta, more time for science at Vesta, potentially a later departure date for Ceres, and a more rapid transit to Ceres. All of this offers the trade of a shorter mission duration – lower cost – for the same science return, or a greater science return for the same cost. A few months ago, the navigation team calculated that every additional 20 Watts directly translated into arrival 13 hours earlier at Vesta, a quantifiable example of increased *mission efficiency* directly resulting from greater power efficiency. On the other hand, that improvement might have been offset by the cost of achieving it, and developing it was beyond the scope of the Dawn Discovery mission budget.



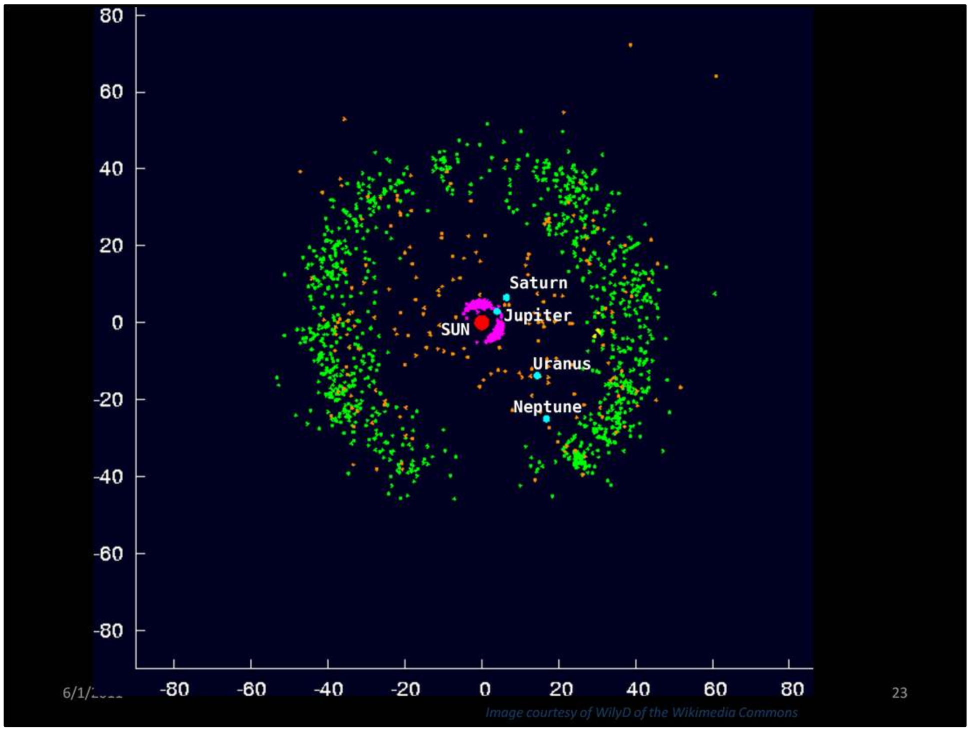
Slide 21: Image of Saturn

As you may know, Plutonium for space applications has become scarce. Solar powered deep space missions – and I'm talking about deep, deep space, beyond the asteroid belt at 3AU, beyond Jupiter at 5AU, perhaps as far as Saturn at 10AU – could be cost-effective alternatives, particularly for multi-body missions like Dawn.



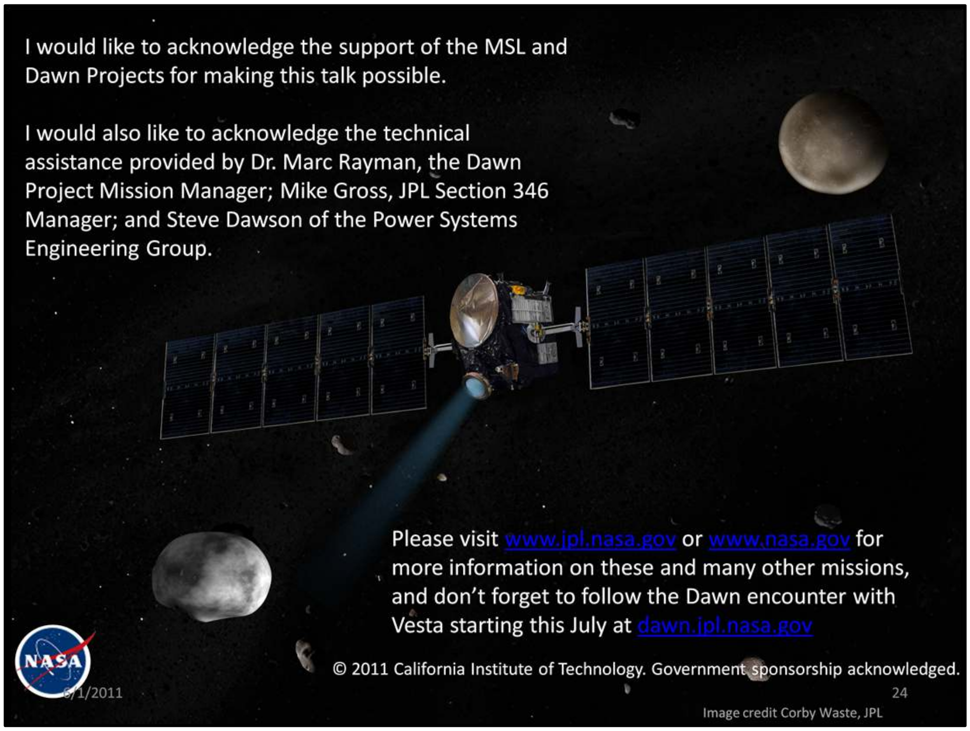
Slide 22: Map of Trojans

What would be the target of such a mission? Detailed investigations of more of the many moons of Jupiter. Detailed investigations of more of the many moons of Saturn. A solar electric *propulsion* mission (a cousin to Dawn) could visit the Jupiter Trojan asteroids, shown in this solar system map as the green dots leading and trailing Jupiter. These are asteroids which share the orbit of Jupiter and might be as numerous as the main belt asteroids or…



Slide 23: Centaur solar system map

We could explore the innermost Centaur bodies (shown in this solar system map as orange dots – for reference the Jupiter Trojans now appear as magenta crescents.) These are mysterious objects, living in odd, unstable orbits between Jupiter and Neptune, and none of which can be imaged from Earth even by the Hubble Space Telescope. One can conceive of a Dawn-like solar electric propulsion mission that could visit more than one of these unexplored bodies. But a solar electric mission to explore beyond Jupiter is certainly out of reach with current design practices. Most ideas for deep, deep space solar powered missions have focused on solar arrays so large we cannot even launch them, or breakthroughs in solar power technologies leading to extremely high power densities. These are not necessarily the next step: Advances in spacecraft power efficiency – advances that are well within our technological capability, if not our current budget – would be sufficient to enable many of these missions at a reasonable cost. These missions are currently not even possible with our current design practices: Improvements in spacecraft power efficiency would enable these explorations, and allow us to explore where no mission has gone before.



I would like to acknowledge the support of the MSL and Dawn Projects for making this talk possible, and for technical assistance provided by my colleagues at JPL, Marc Rayman, Mike Gross, Steve Dawson. Don't forget to follow the Dawn encounter with Vesta starting mid-July at the Dawn website.

Thank you.