Hearing of the House Committee on Science, Space and Technology

"The Exploration of our Solar System: From Mercury to Pluto and Beyond"

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Testimony of Dr. Chris Russell

Dawn Principal Investigator

Professor of Earth, Planetary and Space Sciences

University of California, Los Angeles

Thank you, Mr. Chairman, for providing me an opportunity to review Dawn's recent scientific discoveries at the dwarf planet Ceres; to explain their relationship to an overall planetary program; and to discuss possible future missions of scientific interest in the asteroid belt. I begin by describing the Dawn mission itself since this mission is in many ways unique in our exploration program. Dawn is the ninth mission in NASA's Discovery Program. Discovery missions are Principal-Investigator-led, relatively low cost, focused-investigations that are selected by peer review from proposals submitted by planetary scientists. . The Dawn mission has achieved several important firsts in space exploration. It is the only spacecraft ever to orbit two extraterrestrial bodies beyond Earth, and the only to orbit an object in the main asteroid belt between Mars and Jupiter. Dawn is also the first scientific mission to use solar-electric ion propulsion. Figure 1 shows a Dawn ion thruster.

Figure 1. Ion thruster used by the Dawn spacecraft

Because electric ion thrusters accelerate their fuel more than 10 times faster than conventional chemical engines, smaller launch vehicles and smaller spacecraft can be used. This propulsion system enabled Dawn to first visit Vesta, the second most massive asteroid in the main belt, in 2011; orbit Vesta for a year; and then to leave Vesta and travel to the dwarf planet Ceres. Dawn entered orbit about Ceres in March 2015 and has been mapping it since April. Use of the new technology of ion propulsion enabled us to accomplish more than we could with conventional technology. And it is important to note that we did so at one third the price that conventional technology would have required. Dawn has accomplished what no other mission has accomplished. Other missions have flown by more than one planet but Dawn is the first and only mission to *orbit* two distant planetary bodies.

Dawn at Vesta:

Dawn conducts its investigations by orbiting its target from pole to pole in a set of circular orbits that map the body at different resolutions. It measures the gravitational attraction and thus the mass of the body and the distribution of mass using its radio system. It images in visible wavelengths and in the infrared wavelengths. It maps gamma rays and neutrons. Vesta is the second most massive body in the asteroid belt between Mars and Jupiter. The stretched-color image of Vesta (Figure 2) illustrates the internal diversity of Vesta as reflected in its surface. It is not simply a block of a single type of rock, but it has evolved geochemically to form new minerals after accretion.

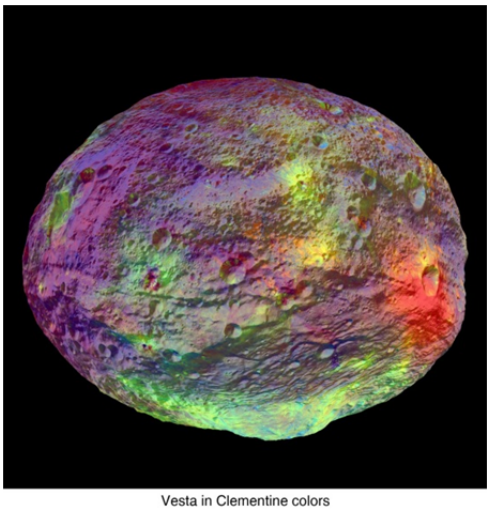

Figure 2. Vesta as seen in color ratios derived from the Dawn camera color filters

The measurements that Dawn completed at Vesta in 2012 were very important in testing our understanding of the origin and evolution of the solar system. Many meteorites from Vesta have

fallen on the Earth. These meteorites have been geochemically analyzed and interpreted, which has enabled us to develop a model of the formation and evolution of Vesta.. Had our understanding been incorrect, we would have predicted the wrong structure for Vesta. However, we found our model was quite accurate and the standard model of solar system formation was secure. Furthermore, we learned much about the structure and interior of Vesta, a body similar to those we believe came together to build the Earth. Thus we learned a little about our planet as well.

Dawn at Ceres:

In September 2012, Dawn left Vesta and headed farther out in the solar system to rendezvous with Ceres, arriving in March of 2015. While Vesta had given scientists on Earth much evidence of how it was formed, Ceres had provided Earth with no evidence that we could recognize or understand. The surface is dark and the topography is muted compared to other asteroids. We expected to see signs of water but could not see any from Earth since water in the Earth's atmosphere hides any Ceres water. Hubble data could not resolve the water mystery either. More recently, the European Herschel Space Observatory reported intermittent signs of water in the very weak atmosphere of Ceres. Further, radar measurements from Earth find the surface to be clay-like, suggestive of the presence of water at some time in the past.

Our initial images of the surface of Ceres reveal a very dry surface, but with bright spots on the surface. We think the bright regions are salt deposits where water has reached the surface and evaporated. As shown in Figure 3, the surface is diverse due to active geochemical and dynamic processes inside. This picture again uses color ratios. Our current thinking is that the surface of Ceres is like permafrost. There is water in the soil but it is frozen. Water is only released during meteor impacts and perhaps other tectonic events. We have some pictures that suggest occasional haze clouds and some scattering of light above the dark limb. So there definitely is a very thin atmosphere on Ceres. At some depth below the surface there should be liquid water.

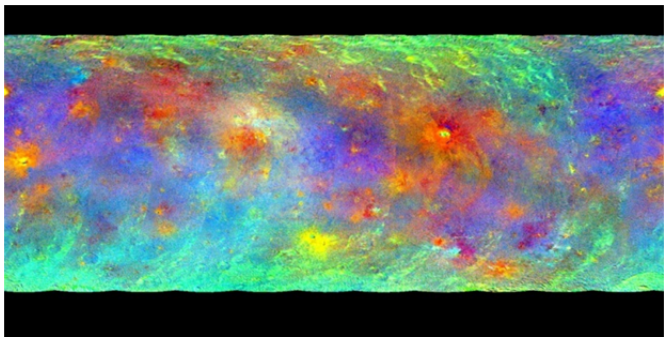

Figure 3. Color ratio image of Ceres illustrating the diversity of processes originating inside Ceres

In many ways Ceres resembles the planet Mars. It is colder than Mars. It does not have as much iron as Mars, as you would expect from the difference in color (Mars is a rusty red; Ceres is dark gray). Both have structures on the surface where it appears that ice once stood and later evaporated. A difference is that on Mars there is exposed ice. We have yet to find exposed ice on Ceres. Figure 4 shows a color-coded elevation map of a large crater on Ceres. The surface appears to be smooth and eroded.

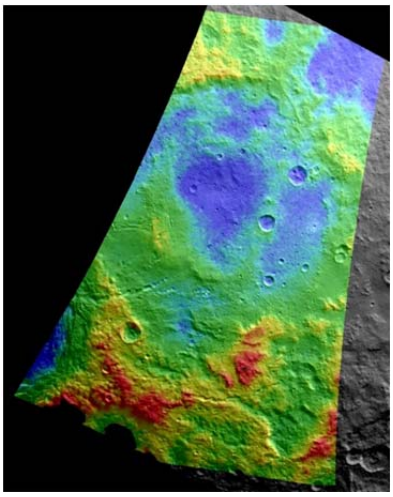

Figure 4. Color-code elevation map showing a portion of the surface of Ceres. Surface has been smoothed by geologic processes giving an appearance similar to that of Mars

Perhaps the freshest and most noticeable surface feature on Ceres is the cluster of bright spots in the Occator crater shown in Figure 5. We currently believe the bright material is salt brought to the surface by water or water vapor.

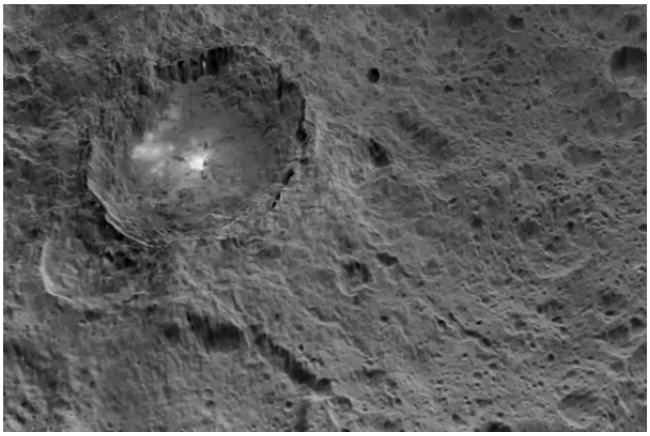

Figure 5. View of Occator crater where brightest spots on Ceres are located

We also have surface features that may be like terrestrial pingos, small mountains covered in dirt with ice inside. These can be found on Earth in Alaska where there is permafrost. There is one large mountain (shown in Figure 6) that is 3 miles high and because of its shape and uniqueness has been dubbed the pyramid. Speculation is that it is like a giant pingo but no one has yet provided good evidence for that theory. Ice pressure could be strong enough to raise such a mountain on a small planet like Ceres. The New Horizons mission detected similar mountains on Pluto.

Figure 6. The so called pyramid on Ceres, a 3 mile high mountain whose origin is not yet understood

Our Continued Exploration of Ceres:

Dawn was designed for a finite lifetime and is reaching the end of its onboard supply of propellants. Thus, it is expected to terminate its exploration program in early 2016. There are two stages of exploration remaining. In September 2015, we will begin our high altitude mapping orbit. This phase of the mission gives us our best model of the surface elevations using stereo photography. We will get more color photography of the surface and spectral information that will help identify the minerals present on the surface.

In the new year, we will move the spacecraft even closer to the surface to the low altitude mapping orbit, where our resolution of the surface is highest. We will also obtain gamma ray and neutron data that can identify the elemental composition of the surface and learn more about the presence of water and ice near the surface. We will also obtain our best information about the gravity field of the planet at this time.

The end of the mission will come when we run out of propellant to point the spacecraft. We need to turn the spacecraft to point at the surface in order to obtain camera and spectrometer data, and we need to point the telemetry antenna to Earth to return the data from the spacecraft. We need to point the thrusters in yet another direction to move closer to or further from Ceres.

When Dawn's propellant is exhausted, the spacecraft will simply remain in a safe orbit for at least 50 years, the time required by planetary protection.

Potential Biological Interest:

Ceres is an object of interest to the biological community. Ceres has water and heat sources from the Sun and from its interior. It might sustain life. Ceres is relatively easy to reach from Earth but does take longer to reach than the Moon or Mars. However, being less massive than the Moon or Mars, landing on the surface should be easier at Ceres. While aerobraking and parachutes are helpful at Mars, they cannot be used at Ceres since Ceres has no substantial atmosphere, much like the Moon. However, retro rockets like used on the Moon and on Mars would work well in Ceres' very weak gravity field.

Future Exploration of Ceres:

The arrival of Dawn at Ceres has raised much interest in further exploration. Dawn has a very elementary payload. There is much more that could be done from orbit and much to be gained from landing on the surface of Ceres. Surface landers could return much information about the nature of the surface and the interior of Ceres. A rover, even a very simple one, would teach us much about Ceres. The biological potential of Ceres can only be best assessed only from the surface. Thus there is much interest on landing on this body.

Closing Comments:

I would like to close this testimony with a short thank you. I have been fortunate enough to participate in space exploration of the Earth, the Sun and the planets during the past half century since I graduated from college. Of course this has been exciting to me personally, but it also has provided a treasury of knowledge about the solar system and a legacy for future generations. I appreciate this opportunity to thank you personally.