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Jo Eliza Pitesky: My name is Jo Pitesky, I'm a member of Cassini's Flight team and your host for today's presentation of Cassini CHARM.

We're going to be looking at several different results from last year's dramatic discovery, confirmation of an ocean encircling the moon Enceladus under its icy surface.

And you have the authors of several seminal papers that were published in the last year, from instruments that are not normally what we think of in terms of making dramatic discovery. These are not cameras, but you'll hear about the evidence that these instruments were able to pull together and assess in order to find that there truly is an ocean.

Our first speaker is (Alexis Bouquet) who's currently a PhD student in a joint University of Texas at San Antonio, Southwest Research Institute Program, working with Cassini's Ion and Neutral Mass Spectrometer, which we call INMS, instrument team.

Alexis started off with an engineering degree followed by working at Airbus in their handling qualities and performance department. As you can see, he's gone through a career change having returned to school, first for a master's degree in astrophysics, space and planetary science, prior to his coming from France to the United States.

In addition to Cassini, he is involved with modeling work for the MAss Spectrometer for Planetary EXploration instrument, also know as MASPEX which will be part of the science payload on the upcoming Europa Mission.

(Alexis Bouquet): Okay, the slide is good. So hello, everyone. So, first, I caught a cold, so I hope I'm not going to lose my voice mid-talk...

I'm going to be talking about some possible evidence of a source of methane in Enceladus' ocean, [it's] some work I did between the University of Besançon, and the University of Texas at San Antonio in the joint program with the Southwest Research Institute.

So, first a few words about the situation at Enceladus, so very interesting if you go to the [next slide] we see the plumes of Enceladus. Enceladus has a liquid water ocean under 35 km of ice. That's one of its most interesting features, the other very interesting features are the water vapor plumes that project into space, and that we believe come from the ocean, that's the dominating understanding of it right now.

So [the plumes are] a great scientific opportunity because it means we get to sample a little bit of what's inside this ocean.

Most of what are in the plumes are not only water, they also contain a host of different volatiles, including carbon dioxide, methane, nitrogen and/or carbon monoxide (they have the same mass [28 g/mol], so they are pretty hard to differentiate), ammonia, and a few others.

Those volatiles can tell us a lot about what's happening in this ocean and what has happened to Enceladus since it was formed.

[Slide 3] First, how do we know? So as Jo was saying, I'm not just watching images and cameras, but rather a mass spectrometer. So we have a sampling of the plumes from the Ion and Neutral Mass Spectrometer of Cassini, that is known as INMS.

As you can see on the right, it has those two openings on the right through which the samples of gas can enter the instrument. The instrument will divide the gas, and will sort out the molecules by mass. And that's how we can get an idea of what is in those plumes.

Of course, this requires the spacecraft to fly through the plumes which it did several times.

[Slide 4] Plume volatiles can tell us a lot about Enceladus. First, [they can tell us] the conditions of the formation of Enceladus, depending on the conditions of pressure and temperature, or you can have a different balance of volatiles. You can expect to know where the materials that formed Enceladus would come from. And also it can tell us, of course, a lot of what's happening inside the plumes right now.

If something is produce, if something destroyed. But, if you care about the origins you have to wonder how is the mixture we’re seeing today representative of the original one. Lots of things could have changed in a few billion years.

[Slide 5] One of the factors that could influence this balance of volatiles, and make one more common than another one, (inaudible), is the trapping in clathrate hydrates. I'm going to call them clathrates from now on.

So clathrates are special kind of ice, it’s an ice where guest molecules (that can be a lot of different volatiles) are trapped in water cages. You see an example on the right of the methane molecule trapped in a clathrate cage. So those red and white molecules are water, and in the middle you see the methane molecule that stabilizes the cage. The guest molecule is what allows this cage to exist.

There are several types and structures of different arrangements of the water molecules, depending on the guest. The formation of clathrates, and their existence require, of course, a lot of water, a low temperature, after all it’s a block of ice, and high pressure. When you consider that you have an ocean on an icy satellite under kilometers of ice, those conditions are likely to be met at Enceladus.

[Slide 6] I actually not only study Enceladus, clathrates are potentially ubiquitous in the Solar System. [They could be] in the cryosphere of Mars, underground and among the frozen water.

On Europa, for the same reasons as Enceladus: lots of ice, high pressure in the ocean, and it's a cold world. Titan also has an extensive cryosphere that could produce clathrates. Pluto, of course, but also, an interesting characteristic of clathrates: you could see them in comets.

So I put here is the image of [Comet] 67P. Some of the volatiles that we are seeing being freed from 67P could come from a clathrate that has been hypothesized.

Comets, of course, don't [produce] very high pressure, the gravity is very low and the comets aren’t that big, but they spend most of [their] time in a very cold environment which is enough to make up for it. And when the comet comes close up to the Sun periodically, it can be expected to heat up a bit, which would develop the stabilizer clathrates, and it would release the volatiles. That would account for some of those things we see from the data of the Rosetta mission but that's an entirely different story. Of course, we are going to focus on how clathrates could form on Enceladus.

[Slide 7] And of course as [clathrates are] ubiquitous in the Solar System, that includes Earth. Clathrates are present on Earth which is not necessarily good news. So methane clathrates are found in sediments in the ocean, remember, high pressure and pretty low temperature. Just as an example of a funny thing we can see do with methane clathrates, which are called, for fun, "methane ice": they can burn. Because if you approach a flame, you are going to melt it. And because the clathrate is going to release methane, methane is flammable, and the flame will keep melting more clathrate and releasing more methane. So you can see ice burning on your screen.

I said [clathrates on Earth] is not really good news because clathrates can be [low in] stability. It can be easy to destabilize. So heating a little bit of the ocean could destabilize them and release the guest, so release a lot of methane, which is a [greenhouse gas]. And we would end up accelerating global warming. That's the "clathrate gun" hypothesis.

[Slide 8] But let's come back to an idea of clathrate on Enceladus and the model we use to know what clathrates could do to Enceladus.

So, we practice [what clathrates could do to Enceladus by studying] a subglacial lake model of clathrate formation, that is aimed at representing how much of each species [of guest] we trap in clathrates in the conditions of a subglacial lake. So in big words: "thermodynamic statistical model describing the guest-clathrate interaction."

What these types of models [will tell you is] what volatiles you have in the water. As a model, it tells you [that] you trap [X] proportion of, let's say, methane in the clathrate, [and Y] proportion of CO2. So that will end up telling you how the balance of volatiles dissolved in the lake is going to change. This model has been applied to Vostok lake, it's a subglacial lake in Antarctica, so on Earth.

The volatiles in the lake at Vostok were supplied by the melting of ice at the liquid/ice interface. We believe that it could work pretty much the same for Enceladus, as a lot of volatiles would be originally trapped in the ice, but over the course of time, because of the exchanges at the interface, they would end up filling the ocean up to the point clathrates will start forming and affecting the balance of volatiles in the ocean.

[Slide 9] So, okay, I promise this is my only text-only slide. What species [of guests] among the ones we see inside Enceladus could be trapped [in clathrates]? So it’s known experimentally what species are prone to being trapped. In Enceladus’ plumes, that would be carbon dioxide, nitrogen, methane (I think you get, by this point, that methane is a pretty good guest for clathrates), carbon monoxide, and hydrogen sulfide.

Also, I did a bit of work on the noble gases, because noble gases are important for Solar System history. Since they don’t react, [since] they are not changed by a reaction, you can use them as a tracer of where materials come from. But of course, if their relative abundances are changed by trapping clathrates, then that's a problem for reading the history of the Solar System.

So, we needed to assess how [noble gases] would be impacted too. But that part of the work took a back seat to what we found about methane.

[Slide 10] So, second question of course: Are the conditions met at Enceladus to actually, form the clathrates and keep them existing. So this is the pressure/temperature graph. The yellow is the part where clathrates can exist, the hypothetic clathrates hosting, primarily, the molecules seen in the plume.

So yellow is the zone where it can exist, and blue is the domain of pressure we expect in the ocean [of Enceladus]. What we can infer from this graph is that below room temperature (300 Kelvin), formation and stability of clathrates is possible at Enceladus.

Of course, Enceladus is not expected to be at room temperature. Most of the ocean would be pretty cold, around the freezing point of water, or even lower, due to the presence of ammonia. So we are pretty safe in assuming that the condition for formation [of clathrates] are met at Enceladus.

[Slide 11] And now, what happens when we run the model? Plenty of things, so the one striking thing, the one that came up in every scenario I ran, what is that? No matter what methane would be depleted compared to the other species.

That's particularly useful; so that means we shouldn't be seeing so much methane in the plumes. It should have been trapped in clathrates.

So dotted or solid lines on this graph represent different kinds of clathrate structures. We expect to supposedly know which structures would preferentially form, but we wanted to cover all the bases.

[Slide 12] But once the clathrates are formed, what happens to them? We calculated their density. It's lower than salt water. Clathrates would float. In a natural environment, clathrates are not even full. So, they will be even lighter than that, there [would be] some empty cages.

So, what would appear is that you would form clathrates near the ice or water interface, where it’s colder, and they would ascend and become a part of the icy crust of Enceladus.

The icy crust is much thicker than the ocean, so it can store quite a lot. Of course, you cannot exclude that some clathrates would be dragged along by whatever the process of formation of plumes is, and potentially reach the plumes in the water/ice trap. You cannot exclude that.

However, given where the clathrates preferentially form, we can expect that a lot of them would take their methane into the icy crust.

[Slide 13] So, the possible explanations for the excess of methane, I already touched on one: clathrates have been dragged along, affected in big quantities, big enough that it noticeably impacts what we are seeing in the plumes.

Or, there could be another process that’s a source of methane, consequently adding methane and shifting the balance of clathrates in the ocean to have more methane. And the source for that could be hydrothermal activity.

Just like the ones we're seeing on Earth, of course, this picture does not come from Enceladus. So just like we’re seeing on Earth, there will be rock/water interactions and ulterior processes involving hydrogen produced by the vents. That would lead to the production of methane.

So, when there are rock/water interactions, we expect to see hydrogen being produced first and foremost. Methane is not the biggest product. So, the following question, of course, is do we see hydrogen in the plumes?

[Slide 14] Answer: Yes, we do.

INMS does detect hydrogen when it flies through the plume, so that's pretty good news. Hydrogen is pretty interesting in that, it’s a tiny molecule, very light. It’s not subject to trapping clathrate; it’s too small to stabilize the cages.

And [hydrogen can’t be stored] in Enceladus; it would have escaped. That means if we’re seeing H_2, it being produced right now. It’s not something that has been produced long ago, being stored and being released now.

That’s pretty good news, but the thing is that INMS sees more hydrogen when it flies faster.

Yes, that seems weird. And the explanation is that when INMS flies through the plumes, the plumes are not only gases, there are also ice grains. Ice grains will impact the instrument, and this instrument is made mostly of titanium.

So the impact can release [atoms of] titanium. And this pure titanium can react with water, [which is] available [from the] water vapor plumes, and the reaction between titanium and water will form hydrogen. So, the hydrogen you see in the instruments, we have no guarantee that it's not an artifact, instead of being actually from the plume.

So, we detect a lot of H_2, a lot of hydrogen. But we cannot be sure that all of it comes from the inside of Enceladus.

[Slide 15] There are some high stakes in trying to sort this hydrogen detection question out because it’s a “smoking gun” of hydrothermal activity. It would be, since [hydrogen] cannot be stored or trapped, it would be a direct estimate of how much hydrothermal activity is going on.

And so, some of those have suggested that the ratio between hydrogen and methane could be indicative of life. Life is much better at producing methane than hydrothermal activity however this is still very controversial, we see very far from being able to make an assessment. And as I explain earlier in talk, the fact that methane can be trapped in the clathrates. And that the confirmation of clathrate is very fat in the liquid medium. That would make the estimate of the methane quantity, very difficult. So we are pretty far from the certainty in this regard.

[Slide 16] So the take-away points for today: Abundance of methane in the plume is in conflict with the fact that Enceladus is a great environment for forming clathrates. Methane should be trapped, however, we see a lot of it escaping. So either clathrates participated in the plumes they were [dragged along and ejected] or hydrothermal activity is adding methane.

The second take-away point is that hydrogen is potentially a gold mine for characterizing hydrothermal activity but it's quantification is still elusive and still the subject of a lot of work.

Well, thanks everyone for your attention and I'd be taking questions if there are any. Thank you.

Jo Eliza Pitesky: Thank you, (Alexis). Cassini -- I have several questions but first let me find out if anybody online has any question for our first speaker.

So let me start with a couple of questions. (Alexis), I was wondering, when you talk about how hydrogen is tested in the INMS chamber which then, working backward, shows that it must have been water ice that had impacted the chamber, was the titanium coating of the chamber initially selected with the intent of being able to make this type of detection, or was this perhaps coincidence?

(Alexis Bouquet): No. First the instrument is made of titanium but titanium oxidizes very quickly in a presence of air. So the instrument was coated in titanium oxide which is unreactive so we were safe in that regard. There shouldn't be a reaction happening, but when INMS was designed, it was aimed primarily at Titan.

We didn't know anything about Enceladus. Voyager had shown that it was a tiny lump ice. So it was not one of the primary targets of Cassini at all. Titan was all the rage at this point, Enceladus and the plumes were a surprise. So at no point was it expected that we would have to deal with this problem at Enceladus.

Jo Eliza Pitesky: So some happy serendipity. Any questions online?

(Alexis Bouquet): Yes and no. It's happy because the impact has allowed it to determine the deuterium to hydrogen ratio at Enceladus, but also it fully muddies the water when it comes to determining how much hydrogen we are actually seeing from Enceladus?

So there was good news and bad news in that.

Jo Eliza Pitesky: And a follow-up question to that, how is this result informing the design of the instrument that you, and I'm guessing Hunter Waite, are working on for the Europa Mission? Of course what you can say or can't say, given that this is only very early days.

(Alexis Bouquet): Yes. I know this question is being discussed. First, the titanium is very unlikely to be selected this time. So the intention, as far as I know, for the material of the antechamber of the [mass spectrometer] hasn’t been decided yet. But it will be kept in mind that it must interact gracefully with ice grains because we are hoping to see similar plumes at Europa

And so [a computing model] is being developed to account for those impacts in the antechamber, to model the reaction happening in the antechamber of INMS. This model can be adapted and probably will be used to predict what reactions could happen in the Europa instruments. So it's a good example of a lesson learned that we can carry on to future instruments.

(Catherine Laurie): And this is (Catherine Laurie) in (Louisville). How does the concentration of clathrates on [Enceladus] compare with what you find as Titan, on Titan?

Male: Excuse me, could you repeat the question please?

(Catherine Laurie): How did the concentration of clathrates that you found compared with what was found on Titan?

Male: What do you mean? You mean the ratios also guests in the clathrates at Titan?

(Catherine Laurie): Were you finding more clathrates on Titan or on Enceladus?

Female: I can't ...

Male: I can't ...

Jo Eliza Pitesky: Sorry go ahead.

Male: Go ahead.

Jo Eliza Pitesky: Oh I suspect one of the difficulty here is that it in this particular case, CDA [the Cosmic Dust Analyzer of Cassini], which is a direct detection instrument, as opposed to something which is working as an imager. Because they were able to detect these actual clathrates coming off of the surface of Enceladus from the interior because of the plumes, they were able to make this measurement in a way that would not be possible at Titan.

Because when we plan Titan science for the most part, actually, CDA tends to be a very minor player. I don’t know. I'm looking at Marcia Burton who is one of our Magnetospheric Plasma Science Scientist and I'm wondering, is there any CDA results looking at this from Titan?

I think the clathrates work has been primarily models. I'm not sure how much has been done on Titan.

(Marcia Burton)

I'm sure there's no CDA data. I mean typically when we're at low altitude, we articulate away and trying not to get all that stuff. So the CDA guys that are online would probably have to answer that question. What's known about that but typically we're not measuring.

Jo Eliza Pitesky:

So good question (Catherine) and one that we very much like to know the answer to, but it looks like we're going to need several instruments in order to establish that.

(Catherine Laurie): Thank you.

Frank Postberg: It's (Frank). Frank Postberg from CDA. I don't think clathrates have been observed from Titan at all. I mean neither from INMS nor CDA. CDA doesn't assess the composition of the Titan atmosphere at all, as you were implying. So I don't think INMS has detected clathrates but INMS has probably detected methane in Titan’s atmosphere. So you could possibly compare the methane abundance of Titan and Enceladus.

Jo Eliza Pitesky: Thank you (Frank).

(Alexis Bouquet): Yes. Modeling clathrate formation [on Titan, as seen] on Enceladus, is within reach from a modeling point of view. As for the data, to my knowledge, there is no firm detection. Also, methane in Titan could be the object of a cycle and its current abundance [will not] stay forever. Actually there have been several events in the history of Titan where methane was released and clathrates could have played a part in that.

But on my end, the modeling work of the Titan is still in its beginning.

Jo Eliza Pitesky: Any other questions for our speaker? All right. Alexis, thank you very much, and we are ready now to move on to our next speaker.

Jo Eliza Pitesky: We have an introduction: We have two speakers for our next presentation. So, in alphabetical order, Sean Hsu, who is base as Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder. He is a member of Cassini's Cosmic Dust Analyzer, or CDA, team. Sean received his Ph.D. from the University of Heidelberg, where his thesis addressed dynamics of Jovian and Saturnian Stream Particle. His research interest, include planetary rings, cosmic dust, planetary and cometary [bodies], and, of course, Enceladus. And I must say that the first time I heard discussing this result was over NPR.

Our other speaker on the same presentation is Frank Postberg, who I've not yet heard on NPR, who is the planetary scientist specializing in cosmic dust and outer solar system science. He is the professor in the Chemistry and Geosciences Department at the University of Heidelberg, and a member of the scientific staff of the cosmic dust research group at Stuttgart University.

Frank is a Co-Investigator for Cassini's Cosmic Dust analyzer, CDA. I'm getting my instrument straight this time. In addition to being a co-investigator of the Surface Dust Analyzer or SUDA which is on NASA's upcoming Europa Multiple Flyby Mission. Earlier in his career, he was a member of the Interstellar Preliminary Examination, ISPE for the Stardust sample return mission. Gentlemen, all yours.

Sean Hsu: OK. Hi, can anyone hear me?

Jo Eliza Pitesky: Yes.

Sean Hsu: [Hsu slide 1] OK. This talk will give by me and Professor Postberg. And so, I will begin the following and [please let us know] if you have any question for him or you have some thought you'd like to share. So this is about the result published a year ago, based on the CDA detection of stream particles, and the story how these particles are formed and what they can tell as about the interior of Enceladus.

[Slide 2] So, we have a slide showing the configuration of the Saturn system, its moons, and the rings. Cassini [has flown] all around [and] has passed through several close flybys of the moons, providing us a lot great images, in-situ measurements, and detailed information [about the up-close] environment. In the panel at the top, you see the relative size of various moons, and you can see that it is actually hard to find Enceladus because it’s actually not a huge [moon].

So you find at the slightly left-hand side, next to big yellow thing called, "Tethys." So Enceladus is rather small, but actually is set in a very interesting position, I think, and you can see that below. Its orbital location coincides with the brightest part of a diffused ring called Saturn’s E-ring. The E-ring is very diffuse but it covers a wide span of space, covering from the orbit of Mimas, a distance of about three Saturn radii, all the way to Titan which is about 20 Saturn radii.

[Slide 3] And the brightest part is located at Enceladus, which makes people wonder if it is the source of the diffused E-ring. And this question was not answered until the Cassini mission, and some of the great images shown here. At the upper right hand side, you can see the backwards scattering of light.

The Sun is behind Saturn and Cassini is taking this beautiful mosaic showing the diffuse light on this micro sized ice grains in the E-ring and the brightest part is the orbit of Enceladus. And zooming in to the left, you see that there's a bright part of [reflecting] dust fitting into these bright arcs of the E-ring. And zooming in further, you see this vision of Enceladus with jets – plumes composed of several jets and also some stars tracks behind. And all this bright stuff you see is actually dust or ice particles.

And that's the main task of CDA [examining these particles]. So we are covering part of this, and that has actually provided us good information about what's beneath the plumes of Enceladus.

[Slide 4] Let's get back to Cassini a little bit. Cassini has a nice suite of instruments. So you have remote sensing package that covers a wide range of wavelengths. We can see them as various telescopes [and other instruments] on board, and that they can look very closely compared to the telescopes on Earth. So they provide [progressively] high spatial resolution and spectral information that can tell us a lot.

And on the other hand, we have in-situ measurements. In-situ means in its original place. That is, we have to fly there and take measurements from there [as opposed to sensing from afar]. So that's the major difference between astronomy and planetary science: we [planetary scientists] can get there and make a very detailed study of the material, right there.

[Slide 5] You must have seen these images above from [Cassini's] cameras. So, from the left, you have Enceladus with several different terrains. You can see there is heavily cratered terrain on the upper middle part, and also, there is some ridges at the lower left part, and below at the southern part, you see the four parallel stripes -- parallel structures called tiger stripes.

And in the middle, you'll see the overlapping of in the infrared image of temperature on top of the optical image, of a scale of about 100 kilometers wide. And you can see that the tiger stripes are actually fits right in the location where you see the hot temperature.

And zooming in further, you see these structures [a tiger stripe], actually very narrow. These are where the particles are emitting, as you can see in the right most figure.

In the plumes of Enceladus, we have a lot of different materials. We have solid components. We have gas components. So why don't we have liquids? They cannot be stable in the conditions [of Enceladus's plumes].

[Slide 6] So an instrument of Cassini, as you have already heard from Alexis, is the INMS instrument which measures the gas component in the plumes of Enceladus.

Mostly, the gases are water vapor and also some primordial gas components like CO_2, like ammonia, like methane that has been reported. And so I will not address this further, but I would like to draw your attention to the solid components [of the plumes].

[Slide 7] The plume dust, of course, [can be seen in the image to the right]. So those reflect the particles micrometer size or bigger that are effectively reflecting or scattering sunlight, and they can form these nice plume images if you look at them at the right geometry. Of course, they will be detected by the Cosmic Dust Analyzer. And I will address that a bit later.

And also during the plume fly-by, a lot of Cassini instruments also detected them unexpectedly because of the very high density, and very extreme conditions there. And the plumes of Enceladus as we know them, are the main source of the defuse E-ring around Saturn.

[Slide 8] So let's take a closer look at this instrument, the Cosmic Dust Analyzer. You see the photo of the instrument, it has a shining gold color, the cylinder is about 50 centimeter in diameter and that is an impact-ionization detector.

The working principle is that you have a piece of dust particles or any materials that are coming in, and eventually it will hit on the target of instruments and with a few kilometers per second speed. And that kinetic energy is transferred into the dissociation, fragmentation, and also ionization of the materials from the instrument target as well as the particle itself.

By analyzing this plasma component, we can separate it with an electric field and we can analyze the charge detected compared to the calibration in the laboratory experiment. [Using this comparison,] We can provide good constraints of all the compositions as well as their masses or sizes. So the composition information is acquired by Time-of-Flight (ToF) Mass Spectrometer.

The ToF Mass Spectrometer has a moderate spectrum resolution to provide us elementary composition information. Also, another important aspect is how much plasma is produced from the target impact. From the lab, we know that the amount of plasma production, as marked in the center yellow box, is proportional to the dust mass times the velocity of impact to a very high power, 3.5 power and higher. That means, with wide range of impact speeds, of the spacecraft’s speed, we can actually cover a lot of particle sizes because that's within the instrument detection limit. So you can see micron sizes and slightly bigger particles and we can see particles slightly smaller than that, and if these particles are really fast, we can even see nanometer particles.

And the particle size coupled with composition provides us with very important information about the dynamics. Because those with different sizes will have different [dynamics, and the forces acting on them] are different. For example, for very large particles, you can imagine that it's like a moon, so it will follow [orbital and rotational paths] and without even feeling the magnetic field or radiation pressure. But for very tiny stuff, like nanometer particles that are [dominated by electromagnetic force], their dynamics would be very different from the big ones and actually, it would be quite useful information.

[Slide 9] Let's take a look at the big particles first. So these are measurements made by CDA, from Cassini's course in the E ring. On the top, you see two CDA Time of Flight Mass Spectra, so two typical spectra for two different populations of E ring ice grains. The majority of them are represented by the left figure, that is the sodium [salt] poor ice grains. So what you see here in the horizontal axis is mass or time, as the heavier impact-generated ions would take longer to reach the detector. That is how the Time of Flight Mass spectrometer works. So it takes us a series of math [equations to calculate mass as a function of time]. And you can see these forests of water clusters that are from the impacts of ice grains. And in addition to that, you can also see a series of additional peaks that are actually the sodium plus the water forming a cation that is attached to water cluster ions [with about equal distance between peaks].

And at the right, you see a very different look in spectra that is actually also [showing] water ice particles, but the salt content is very high. So it's about 2 percent for the salt content. So that is slightly lower than the salt concentration in earth's ocean [3%]. Because sodium is very easy to ionize in the ionization process, it shows [significantly different] features in the mass line of the time of flight spectrometer [measurements].

These are actually minor components in the E ring, but the presence of these salt-rich grains are actually significant because, as you can imagine, when the sea water in the arctic region gets colder and colder, it starts to freeze. You would not expect salt in the ice content. To form these salty ice grains, that means you must have a direct, liquid water source to provide the existence of the sodium rich ice grains.

And the other information we have is about the dynamics. So, as you can see below, there is a simulation, a dynamical evolution simulation, of particles of 1.4 micron radii coming from the surface. And so you can see here, dynamic evolution times are rather long. It takes several years for their orbits to evolve due to the forces by gravity, by electromagnetic forces, and by radiation pressure. And from here, people can actually constrain, what amount of particles you need to replenish the loss of E ring grains and all these [constraints] came [up with a] picture like this.

[Slide 10] At the right you see this schematic of the profile of Enceladus along its south polar region. From gravitational measurements, people interpret that there's a layer of big water beneath the South Pole and between the ice shell the rocky core. And from there, the existence of salty ice grains provides us with the right information that water is actually going right up to a near-surface plume source where they could form these bursting bubble scenarios. So you can imagine, if you have gas dissolved in the water, as the pressure decreases, it's like when you open a can of soda, the gas starts to [release] from [being dissolved in water], forming bubbles.

It will eventually burst and provide small particles or big particles, and under low pressure, these will quick or fast freeze into the storage particles that you see in the [salt-rich] mass spectra. And these [salt-rich particles] are actually heavier particles compared to those formed from the vapor condensation, where the water vapor gas is upwelling from the vent, forming the plumes of Enceladus.

We see clearly two components, or different subcomponents, with different sizes and compositions. That tells us how different types of ice grains formed from the vents of the plume, and how they composed their relative fractions of the E-ring. So these are for the bigger particles, or the bigger ice grains… [Those are from] water surfaces exposed to almost vacuum and forming the gas column into the vent, and forming these ice grains. It's quite unique in the Solar System as we have it.

[Slide 11] Now I would like to take your attention to smaller parts of the (dust) that we see. So these are called “stream particles.” These are nanometer-scale particles of that are traveling with very high speed. These types of particles, tiny and fast particles, were first seen in Jovian system, but it was predicted that they could also be detected at Saturn, which is the case as you see in the bottom. Before Cassini even reached Saturn, the cosmic dust analyzer already started to look for materials coming from Saturn.

The detection rate of these tiny particles gets higher and higher as the spacecraft approaches Saturn as you see the [horizontal] axis is time, in the year 2004. And, the rates got higher and higher as the spacecraft was closing in. And also you see burst-like [distribution]. So they are not continuous blocks of particles but they show a high flux, which later has been found to correlate with the solar wind conditions.

And, on the composition point of view, it was quite puzzling from the beginning. We know that in Saturn's systems, the surface of the moons and the ring [particles] are actually made of water ice, the majority of them, or more then 90 percent of the surfaces, are water ice.

However, the particles show a consistent silicon mass line, that is actually the only particle constituent you can see from these particles. So the carbon peak and the rhodium peak, while they are strong, they are most likely from the surface of the targets of [the instrument] which is not originally from the particle. And the other thing to note is that they are extremely metal poor. They are silicon-rich, and they basically show no trace of metal, which is quite unique because in normal rock-forming materials, they are all metal silicon oxides.

[Slide 12] So, what we know is that, these particles, because they are silicon rich, they're mostly from rock-related processes, [i.e.] they must form the rock with additive processes, but they are not typical rock-forming minerals. And from the Dynamics point of view, their solar interactions and also their high speed tells us that they must be very tiny.

[Slide 13] And from the interactions of these particles, we have done the simulation with this bluish sheet [on the slide] from (Saturn). We simulate how they react to the changing of the solar wind in dynamic situations.

[Slide 14] And from there, it can tell us what is their kinetic energy and their size, or the escape velocity. So showing on the upper plot is the probability derived from those exercises of the particle's sizes shown in the horizontal axis as well as the speed where they escape the Saturnian system.

And so you can see a belt covering a wide range, of about two nanometers to about eight nanometers in size, in radius. And from here, what we can actually convert, via the conversation of energy law, is how much energy they can gain from the magnetic field of Saturn if they are charged positively. And from the plasma measurement in the magnetosphere, we know there's a region where grains are preferably charged positively, outside of about seven Saturn radii.

What we can calculate is the kinetic energy of these particles derived from the solar reflection to the starting position where these particles start to gain energy and escape from Saturn. And so, what we got is the blue [curve] shown in the bottom plot. We have also done the forward modeling, that is launching particles from the E ring region [shown in the red curve], and one can see it's a similar pattern. What this tells us is that it's actually a broad region. What we see, then, is not from a single plume source.

So they are from a broad region in Saturn’s E ring where the grain charge polarity is preferable for them to gain energy to escape. And, we came up with one explanation for this:

[Slide 15] these particles are not directly from any of the [plume] sources, but they are from the E ring. So these particles are most likely nano-phase silica inclusions embedded in the E ring, in the micro-sized E ring.

After the E ring escape of the plumes of Enceladus, the E ring particles enter the orbit of Saturn, and their orbits evolve as a function of time. Meanwhile, the plasma ions in the magnetosphere start to erode the E ring ice particles. There's a process called, differential erosion, that is the silica particles are sputtering or erosion-resistant much more than the water ice that surrounds them. At some point, the water ice will erode away, and these nano-silica particles, which are more stiff and sputtering resistant, will be released from the E ring grains, and start their own dynamic evolution.

And eventually if these particles are released in the region where the plasma environment allow them to be charged to the right polarity, to gain positive charge, they can gain energy from the magnetosphere and escape from the Saturnian system. And that explains how we see these particles and the origins of these particles. Of course the origin of the particles implied here is that, Enceladus is the ultimate source of those E ring ice grains as well these nano-silica particles.

Let's make just quick stop here, if anyone has any questions about what I just said.

If not I will proceed. [Slide 16] Right now we know the nano-silica particle, we know they are from Enceladus, but what does that tell us? We know they are nano-phase silica, but as a dust source, they can form in a different way. So they can form from top-down process or bottom-up process. So top-down means, for example, a process like fragmentations, you grind a bulk of silica into smaller and smaller particles. That's one way to form nano-silica particles. Or you can form them molecule by molecule, attaching to each other and form them from the bottom up process like synthesis of colloids, as people widely know.

And the other constraint we have is that this particle has a narrow size range. The other thing is that, because they are inclusions in the E ring range, they must form before the ice grain in the E ring before they end up in the plume. So they pre-exist the source of the plumes of Enceladus, so what we may find is a process that can form a narrow size range of nano-silica particles within Enceladus.

[Slide 17] We see fragmentation is less likely because it will, as shown in this [image] in lower left, will always produce a broad range of sizes.

And that is not consistent with what we saw, and, from the industry and a lot of other studies, we know that to from uniform sizes of nano particles, the best way is to build them up from the bottom. And one of the most likely processes, we think, is from hydrothermal reaction. Silica and water systems are very unique. As you all know, if you put sugar in hot coffee, as the coffee gets colder and colder the sugar, if you did put in a lot, will precipitate out as a solid again.

The dissolved components of sugar will precipitate out at lower temperatures as long as the solubility temperature is reached, [i.e. as long as the water is saturated with sugar] at that temperature. But, with silica, there is an intermediate stage where before they precipitate, they form a stable phase of nano-colloids. These nano particles could form stably and, because they are so tiny, they can be suspended in the water. You can see this in the middle figure, that the whitish, the milky color in the water is actually silica colloid forming from a hydrothermal reaction.

And if you have enough time and proper conditions, they will precipitate, forming much larger structures like precipitation.

These processes, the kinetics of silica nano-particle formation have recently been well studied in the lab as well as in theory. From terrestrial studies and then also some studies on Mars, we know that silica is indeed an indication of hydrothermal reactions on Earth and any terrestrial planet.

[Slide 18] In this case, the silica particles are very useful to provide the conditions within Enceladus because there is only a certain range of conditions in which they could form and exist stably. So one of them, one we can constrain is the pH, the alkalinity or acidity of the subsurface water of Enceladus. So this plot shows how stable these silica colloids are as function of pH shown on the horizontal axis. So you can see that, silica is stable at basically pH above seven to about eleven.

So in this range, these colloid silica particles are charged negatively on their surface so they can repel each other, not aggregating to form large enough particles to precipitate. And there's a metastable region at about pH of two, but I think that's not the case we have here, as the salt rich particles [from the plumes] also infers the alkaline pH range.

So this is concerned with the measurement of big grains, and the other thing that we can constrain and can be compared to the larger, salt rich particle measurement is that silica colloid particles in the solution will lose their inner charge if you put too much salt in it. This comes about from the salt which can attach to the negatively charged side of the particles causing them to lose their charge, so aggregation will perform much more easily with a lot of salt.

[Slide 19] To have individual nano-silica particles from the lab, we know that the salinity, the salt concentration, shouldn't be higher than 4 percent. And this is actually a very important conclusion because it rules out that a coagulate would form at a much earlier phase because, as you imagine, the cooling of the mixture would eventually lead the solution into a brine phase where you have a very high concentration of salt in your solution. And nano-silica will not survive that kind of condition, that means that these particles we observe must have been produced recently, in a geological time scale.

[Slide 20] Another thing that's very important, and that would take some time you explain, is that, we can actually constrain, what is the rock composition to form these silica particles. So in this figure on the left, you see a modeled silica concentration and measured silica concentration as a function of temperature and pH values.

For different rock materials, the solid lines represent the silicon-rich rock in the experiment, and different pH is shown in green, blue, and black as pH 10, 9, or 8. So alkaline pH in increments of one. Silicon-poor cases are shown in the dashed lines, and the circles, the black and grey ones, are from the long-term hydrothermal experiment carried out by our Japanese colleagues from the University of Tokyo, Professor (Shakina) and his team, have performed long-term, hydrothermal experiments. They put rock powder of different kind into solutions of different pH and cooked them at high temperature, high pressure compared to Enceladus' interior for months, measured at [the beginning, middle, and end] of the experiment.

That provides a very good constraint and a very good compliment to the observations of CDA. We can see that the horizontal dashed lines of green, blue and black are the solubility of silica at zero degrees [Celsius] with respect to the temperature at the source of the plumes at different pH.

We can see that only with experiment of silicon-rich rock composition, you can produce silica solution, [i.e. the] silica concentration is high enough to form some of the silica [precipitate]. So, the silica concentration must be above the solubility of silica at zero degrees to form nano-phased silica.

So, the silicon-rich material or rock is representing a primitive type of rock. It's not like a differentiated case like Earth's mantle, and that actually tells us the core of Enceladus is not highly differentiated and it's most likely porous.

[Slide 21] In the experiment, they also found nano-phased silica as they extracted the solutions from the experiment. The size is perfectly matching what we see, or rather, what we inferred from the CDA measurements.

[Slide 22] Moving on, we can also provide some constraints on the temperature of the reaction. As you remember from the previous figure, everything depends on temperature. So, if you want to dissolve more silica, you need to have higher temperature.

So, what we can do is to provide a lower limit constraint on the temperature, but that is also complicated by the fact that the change of the pH will lead to change of the solubility of silica, and therefore we must consider both factors in this case.

We came up with two scenarios: disequilibrium and equilibrium scenarios, and that refers to [whether] the hydrothermal fluid is in equilibrium with the ocean water around it [or not].

For example, the first case, the hydrothermal vent systems in Earth's oceans are disequilibrium cases, i.e. the chemical property and composition of the hydrothermal fluids is very different from the ocean water. And in that case, if you look at the right figure, we can derive the minimum temperature [required for nano-silica formation] for a given pH, the alkalinity, of the hydrothermal fluid and the sea water.

So, if we assume a [hydrothermal vent] pH of 9, and in this case, if the hydrothermal fluid is not in equilibrium with the seawater, the pH will drop on cooling. Meaning that, for example, if [the seawater pH] is dropped from a 9 to 8.5, for silica to stably survive, you need a temperature of 140 degrees Celsius.

And if it is a case that the hydrothermal fluid, and the ocean, and the icy crust [ice shell] are actually close to chemical equilibrium, that's the lower case [in the slide], then we will expect the water composition, the subsurface water composition of Enceladus, is actually governed by the rock-water interactions.

So, if that is a whole closed system, that the water and rock will mix into equilibrium conditions, then what we see in the plumes should be the subsurface ocean composition.

And in that case, when the hydrothermal fluid cools, the pH most likely will rise. So, for example, find the light blue curve of pH 9, that is the hydrothermal fluid pH. And once [the ocean water] goes down to a pH 10, you would require even higher temperature because higher pH values will [decrease the water's ability to dissolve silica], so to reach saturation, you need a much higher temperature to dissolve much more silica.

[Slide 23] And last one, last constraint [this study] provides us is the stability over time. As you can imagine, these nanoparticles will not be very stable over time. So, from lab experiments, we know that these colder particles in the solution forms initially with a radii of two to four nanometers. And then they will grow slowly if they are put in the right favorable condition. They will grow slowly by Ostwald ripening.

Ostwald ripening is actually a daily phenomenon you can see. If you put oil and water together, you will see that oil particles or patches growing bigger and bigger by absorbing smaller oil particles. And that's a similar phenomenon for nanoparticles as well.

This process, we can actually quantify and provide a constraint on how fast they can grow into sizes that we don't observe. For the size ranges, we observe, smaller than 10 nanometers, are mostly likely formed recently in the Ostwald ripening process. So within one year, they must have formed from the saturated solution and then transported upwards to the E ring grains.

This also implies a very fast upward motion to transport them from the bottom of the sea to the plumes of Enceladus. So, that's about 50 to 70 kilometer in distance, vertically. So, that actually is very vicious convection.

Also, this means these fast convections will most likely provide a quite good mixing of the seawater, the ocean water, the ice crust, and also the core of Enceladus. And so, it is likely to be equilibrium rather than disequilibrium conditions for the hydrothermal waters in the ocean.

[Slide 24] To summarize, this is a figure that shows what we could derive from these nanoparticles as we got from the [CDA.]

[Slide 25] I don't want to repeat all these, but what I want to address is that these different population particles reflect processes at different steps of temperature within Enceladus. So, the larger micro-size ice grains reflect the thermodynamics of water interacting with chamber walls and forming ice grains of different composition near the plumes and near the surface. While the nano-silica dust particles reflect more rock-related processes that connect the porous core to the subsurface ocean and all the way up the plumes.

[Slide 26] I would also like to show you some of the terrestrial analogs. As you may know, most of the hydrothermal vents we find on Earth are not these kind of alkaline hydrothermal vents. They are more like very low pH, or acidic, with a lot of sulfur, and the depositions turning yellow colors. But we do find some particular cases, the most famous one, or probably the only one, is the Lost City Systems that's found only recently, within two decades.

It's very similar conditions to Enceladus. We have high pH and it's right on the mid-ocean ridge (MOR). This suggests that it’s been active for more than 100,000 years. And also, there are some other cases and also that these conditions were more in the early oceans on earth.

[Slide 27] These are some analogs, and that brings us to some most interesting questions: These alkaline hydrothermal events can actually support an ecosystem without sunlight. So, how are they supported? By production of H_2, as mentioned in the previous talk, from serpentinization.

The [energy] H_2 provides these chemical reactions will provide the microbes, if any, to survive the conditions without sunlight and thrive in an ecosystem down there. This kind of system was considered to be a good candidate for life, where life first emerged on Earth or any other places in the Solar System or the universe.

Lastly, I would like to address that this work is following a concept proposed by Professor Grun on “dust astronomy.” Now we are using dust [in a whole new way]. We are using [dust] as a tool, like photons in astronomy, to detect conditions and their sources, which cannot be shown otherwise.

As the exploration of planetary systems continues we’d certainly like to apply this approach further to other interesting systems like Io, Europa, Triton, and other worlds.

And with that, that's it. I'm happy to take any questions and we are happy to take any questions. Thank you.

Female: Thanks very much (Sean). Any questions first from the virtual room?

I did have a question about especially the last slide because, always, I'm curious about the astrobiology implications. And when you say going out to Io and Europa, and then further out to Triton, how far do you imagine we could really push this kind of model going out in distance from the Sun?

(Sean): Well, this work, most likely, does not really depend on the distance of the Sun, but [depends on] the solid phase of the materials, which could have very different interactions and processes compared to others like gas and plasma. That will reveal to us some unique opportunities to probe different processes sealed in the solid components of a system. And I think the tool we have is how to examine these particles and combine knowledge from planetary science. We could apply this anywhere.

Male: May I add something? Of course, in this case, the application of the dust astronomy has implications for astrobiology, but because we are possibly probing habitats, at least, a place where the conditions look like they could be habitable. Of course dust astronomy applies also outside astrobiology, and this is what the last bullet [in the slide] implies, that it has a lot of applications.

Male: Could you please explain the word serpentinization?

Male: Okay. Serpentinization, that's an exothermic rock-water interaction. So when you have primordial rock, or rock that has never seen water, which is water free, [when that rock] encounters water, an exothermic reaction starts which produces hydrogen and energy. And this is happening on hydrothermal vents on Earth, and they provide nutrition and energy to the microbes, for example, so that's why it's relevant.

And also, in the case of Enceladus, it could contribute to the overall energy budget of the moon, because, as you know, there's a lot of heat that radiates away from the moon and the some people are struggling to find the mechanism which can produce all this energy, and serpentinization could contribute here.

Female: Any other question for our speakers? All right, we're getting close to the end of our time. So, I'd like to thank everybody very much for attending, and I'd like to thank our speakers again very much for participating. Our next CHARM telecom will be in three months, so the speaker yet to be determined. Thanks all very much. We always appreciate your participation.

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