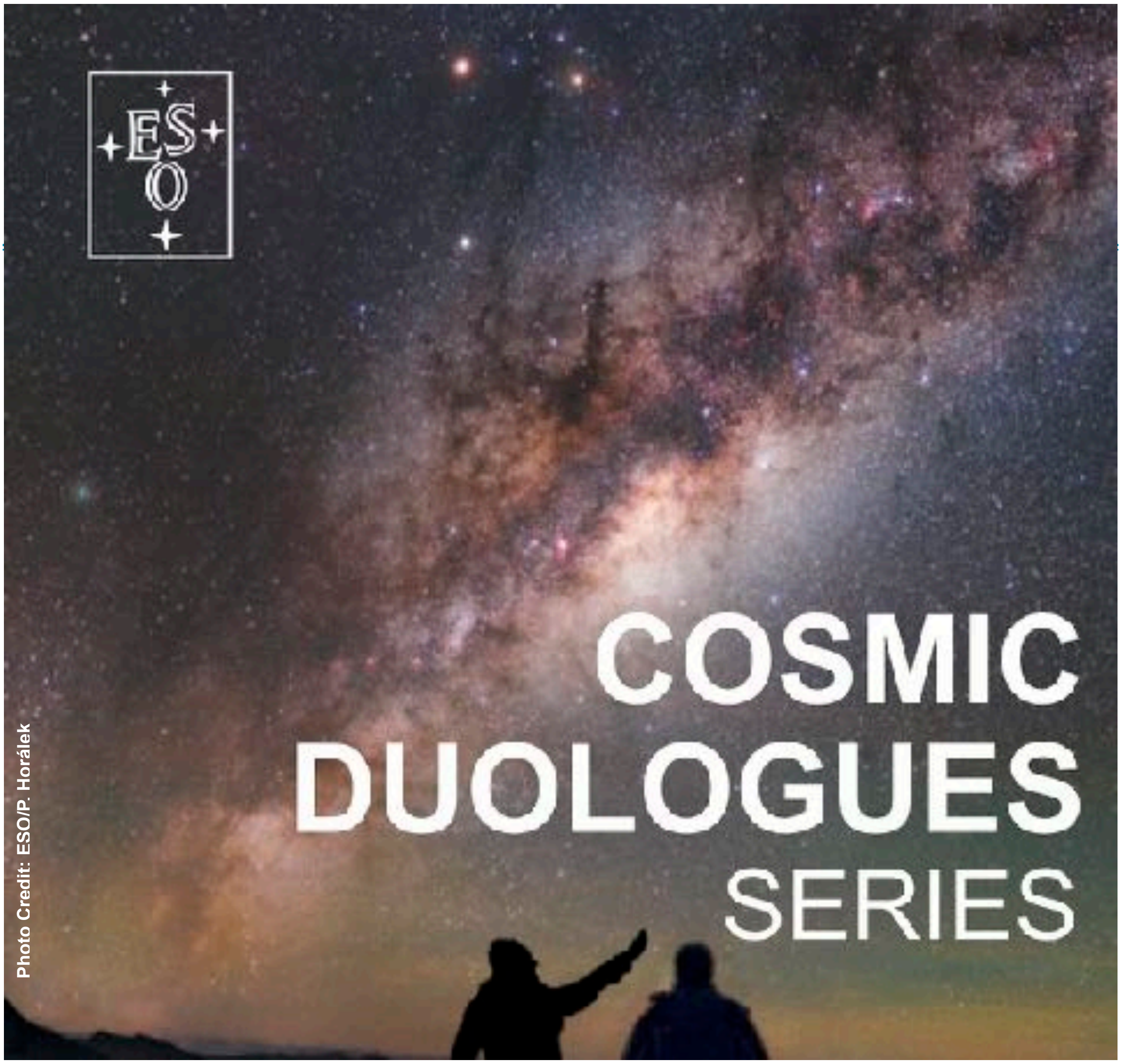

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The Formation and Evolution of the Solar System

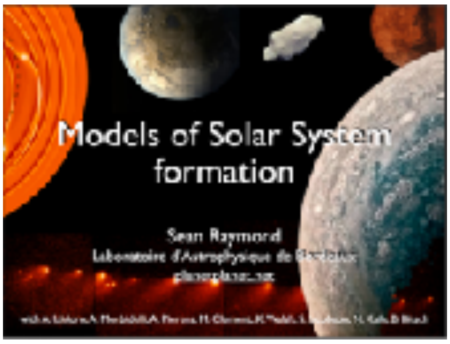
ESO Cosmic Duologue 4 - Interview

8 June 2020

Henri M.J. Boffin & Giacomo Beccari (Eds.)

On Monday 8 June, 2020, the fourth ESO Cosmic Duologue took place. It consisted in a discussion between *Megan Schwamb* (Queen's University Belfast, UK) and *Sean Raymond* (Bordeaux University, France) and chaired by *Cyrielle Opitom* (ESO), about the formation and evolution of the Solar System. Further information on this event, including a copy of the slides, the link to the video of the duologue, as well as to some background material, is available at https://www.eso.org/sci/meetings/2020/Cosmic-Duologues/duologue4.html.

As a follow-up to this successful event, we have asked our two speakers to answer in more details some of the questions raised during the event. This is provided below, where the answers are identified by the initials of the speaker.



Models of Solar System formation

Sean Raymond

Laboratoire d'Astrophysique de

How observations are constraining the formation and evolution of the Solar System

Meg Schwamb

(Queen's University Belfast)

@megschwamb

1. How likely is it to get a double planet (Earth-Moon)?

SR: Earth's Moon is thought to have formed as a result of the last giant impact between its constituent planetary embryos (e.g., Benz et al 1986; Canup 2004, 2012; Cuk & Stewart 2012 – note that one model does propose that the Moon formed as a result of a series of impacts rather than a single one: Rufu et al 2017). Researchers have performed hydrodynamical simulations of the outcomes of the full range of giant impacts between growing rocky planets (e.g., Genda et al 2012; Leinhardt & Stewart 2012), and there is a considerable range of impacts that can produce satellites. I've never seen a full mapping of the parameter space of outcomes in terms of showing the fraction of impacts that produce satellites with mass ratios with respect to their planets above a given threshold, but I believe that sort of study is in the works (e.g., see Timpe et al 2020). On a personal note, I *hope* that double planets are common because they are really cool!

2. What about the role of planet 9 in the formation of the solar system, even if we didn't discover it yet ? Did you consider it in the simulations for different models ?

SR: Planet 9 – if it exists – would be a result of the planet formation process and would not have played much of a role in terms of affecting the formation of other planets. In that spirit one can ask: if Planet 9 exists, where did it come from? Planet 9's orbit would need to be hundreds of AU wide and eccentric to explain the orbital sculpting of very distant Kuiper belt objects (for the latest, see Batygin et al 2019). A few potential origins scenarios for Planet 9 have been proposed and I think there are two plausible models.

The first model is that Planet 9 could have been captured from another star in the Sun's birth cluster of stars. If another star passed within a few hundred AU of the Sun and had a wide-orbit planet – perhaps one that was scattered outward by closer-in, more massive planets – then the Sun could potentially have captured Planet 9. In that context, Planet 9 would be an exoplanet lurking in our own Solar System! However, models find a quite low probability (of 0.01% to, at most, 1%) of the required chain of events having taken place (Li & Adams 2016; Mustill et al 2016).

The second – and I think more plausible – scenario for Planet 9's origins proposes that it was scattered out from the young Solar System. Planet 9 would most likely be a leftover from the formation of the ice giants. We think the ice giants grew through a series of giant impacts among icy cores of several Earth masses beyond Jupiter and Saturn's orbits but that this process was only about 50% efficient and that many such cores were ejected in the process after being scattered by Jupiter or Saturn (Izidoro et al 2015). If a scattered core underwent a gravitational encounter with another star in the Sun's birth cluster, it could have been trapped on a wide, eccentric orbit like that proposed for Planet 9. The details depend on the properties of the Sun's birth cluster, and in the best-case scenario the probability of trapping a scattered core on a Planet 9-like orbit is ~10%. This work was done by Andre Izidoro and Nate Kaib and isn't published yet (Izidoro et al, in prep.).

For an explanation of the dynamical issues related to Planet 9's origins, see a series of posts on my blog, e.g., see *https://wp.me/p3BSYQ-Od*

3. Could the environment in which the solar system formed have played an important role in shaping the Solar System?

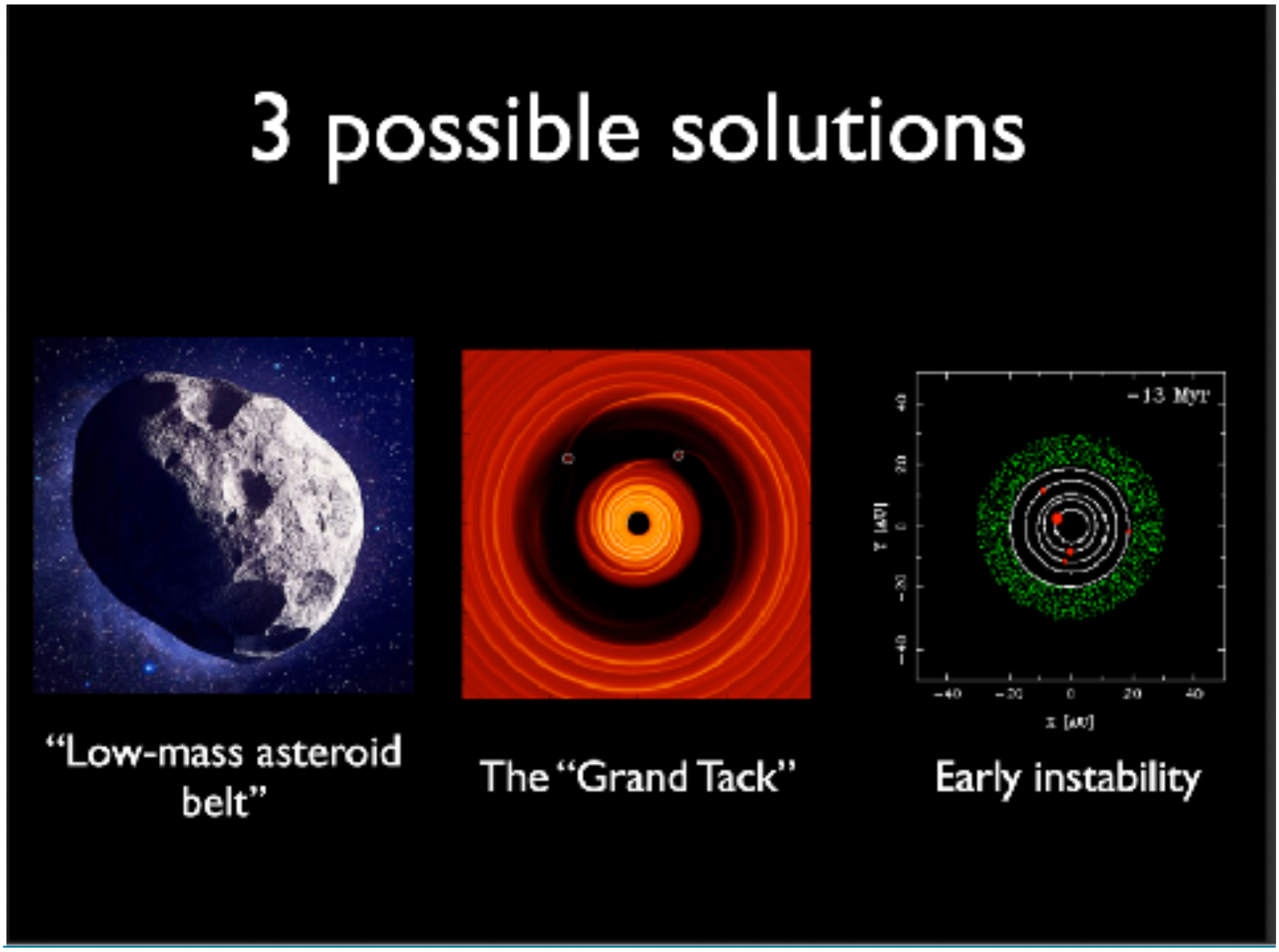
SR: Absolutely! The Sun was probably born in a cluster of roughly one to ten thousand stars, although there is plenty of debate about this (e.g., Adams 2010; Pfalzner et al 2015). Other stars affected the Sun by injecting short-lived radionuclides into the Sun's planet-forming disk (and thus drying out a large portion of the planets’ building blocks; see Grimm & McSween 1993; Lichtenberg et al 2019). Fly-bys of other stars would also have affected the planets’ orbits and those of small bodies in the outer Solar System (e.g., Malmberg et al 2011; Hands et al 2019). Clearly, the Sun did not suffer the passage of another star closer than ~100 AU because that would have disrupted the outer Solar System to the point of not being consistent with the present-day one.

4. Is there currently a/your favoured formation model? What is your main point for preference?

SR: Three models can adequately explain the large-scale structure of the inner Solar System: the Low-mass asteroid belt (Hansen 2009; Drazkowska et al 2016; Raymond & Izidoro 2017), Grand Tack (Walsh et al 2011), and Early Instability (Clement et al 2018, 2019) scenarios (see long discussion in Raymond et al 2018 or this video – *https://youtu.be/cSUrfEErhSE*). Each scenario invokes different physical mechanisms to explain the orbital architecture of the planets and asteroid belt. Each has its own weaknesses, although none (at present) that is sufficient to rule it out.

I don’t think it’s helpful to pick favorites among the models. There is an inherent danger of becoming too attached to a model and treating it as the “truth” rather than keeping a critical eye on it. After we had submitted the Grand Tack paper and I started to present the idea in talks, I was sometimes asked whether I “believed” in it, and I would systematically reply “*no, of course not!”* Models are tools, and the best ones are simply stepping stones in the evolution of our understanding. It’s quite possible (likely, even) that none of the current ones captures what really happened.

That being said, I’ve noticed that different communities naturally gravitate toward different models. Astronomers that work on planet-forming disks and are used to seeing ring-shaped dust



3 possible solutions

“Low-mass asteroid belt”

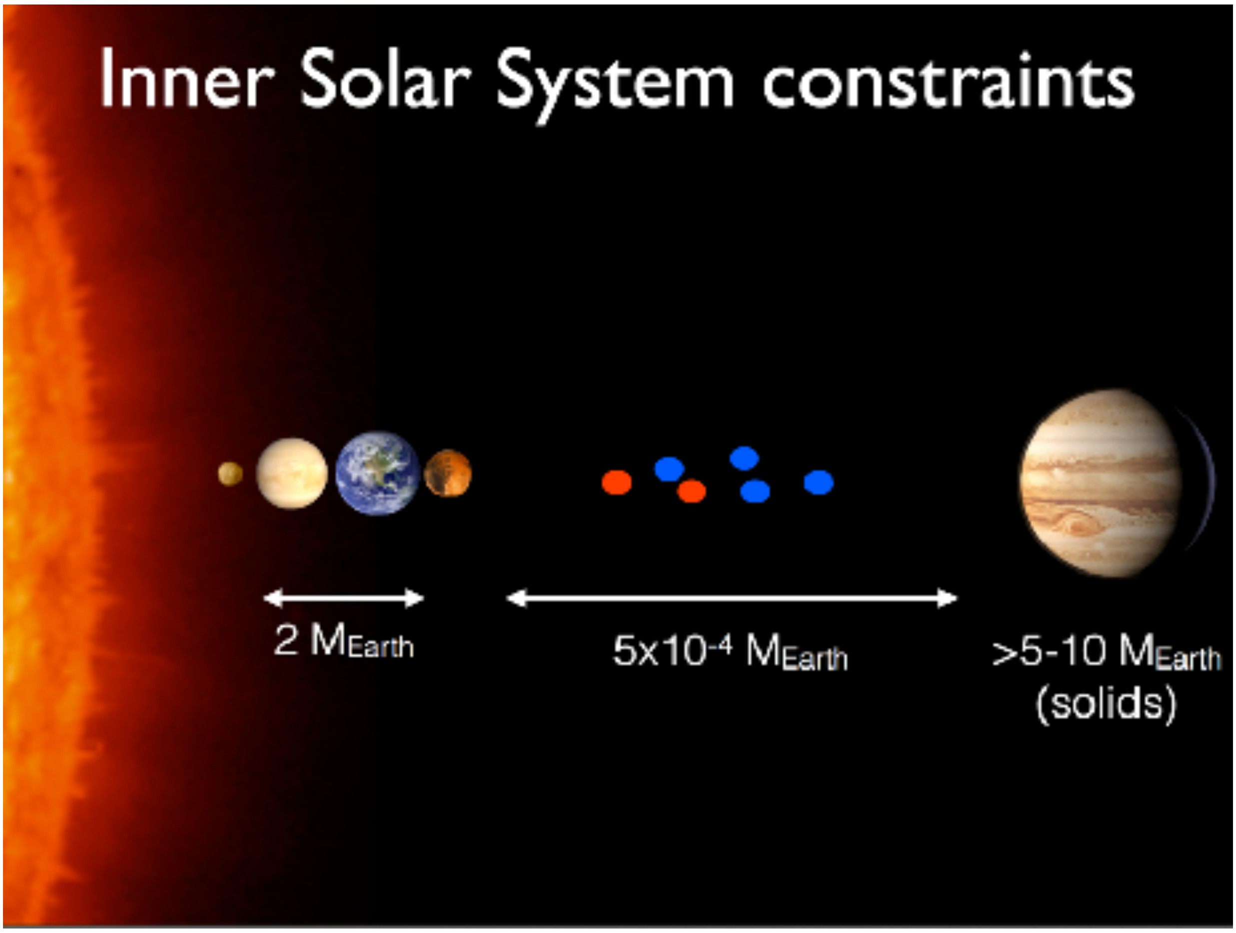
The “Grand Tack”

Early instability

structures are fans of the low-mass asteroid belt model. Exoplanet dynamicists are drenched in orbital migration theory and favour the Grand Tack. Solar System dynamics modelers often favour the Early Instability model as it explains the inner and outer Solar System in one fell swoop.

5. What future observation tests would be most important to address the key questions about planet formation?

SR: Any model that is considered viable already has to match present-day constraints. Hopefully successful models will make predictions that will be testable with future observations. I can't think of one simple observational test to rule out given models, but useful constraints include those related to small body populations in the Solar System, the impact history of different Solar System bodies, and meteoritic constraints on the evolution of planets' compositions (e.g., via isotopic measurements of different types of isotopes – e.g., Budde et al 2019). I also think that correlations between different populations of exoplanets will tell us a lot, for example whether close-in super-Earths correlate or anti-correlate with the presence of outer, Jupiter-like gas giants (Barbato et al 2018; Bryan et al 2019).



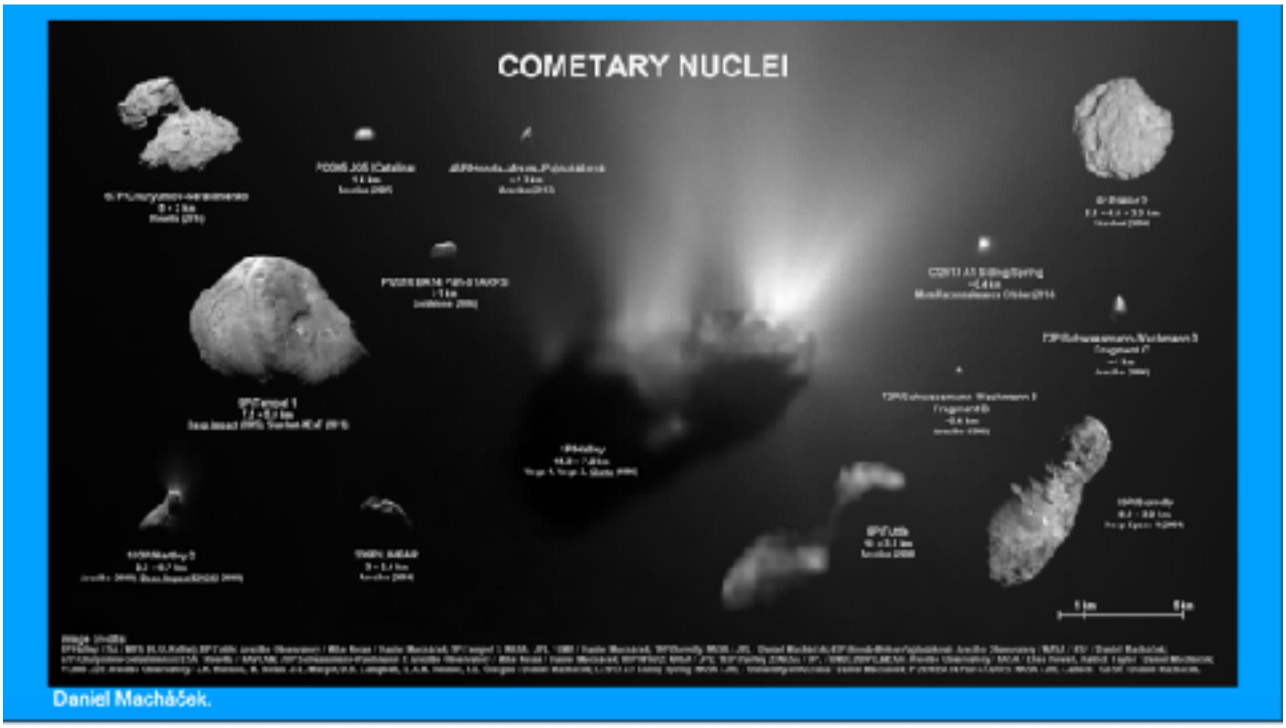
MS: The *Rubin Observatory's Legacy Survey of Space and Time* (LSST; *https://www.lsst.org/*) is scheduled to turn online in ~2023. It will catalog over 5 million Main Belt asteroids, almost 300,000 Jupiter Trojans, over 100,000 near-Earth objects (NEOs), and over 40,000 Kuiper-belt objects (KBOs). Many of these objects will receive hundreds of observations in multiple bandpasses. Getting larger samples of Solar System small bodies with colour and light curve information over the next ten years will be an incredibly powerful dataset. Both to test the predictions of current planetary formation models in unprecedented detail and also find new correlations between the orbital and compositional properties of Solar System small bodies that the models will need to explain.

6. Is there a model that best reproduces the Trojans?

SR: The dynamical instability that is proposed to have taken place among the giant planets (in different incarnations called the *Nice model* or *Jumping Jupiter* scenario) has been shown to nicely match Jupiter's trojan asteroids, including their broad inclination distribution (Morbidelli et al 2005; Nesvorný et al 2013). In this context the Trojans represent outer Solar System planetesimals that were captured by Jupiter during the instability (see Nesvorný 2018 for a review).

7. The interstellar object 2I/Borisov is similar to our own solar system comets. Does that mean the host system of 2I is similar to our solar system in terms of of the giant planets architecture?

SR: All it means is that Borisov was dynamically ejected from its home system. If the ejection happened because of gravitational scattering by a giant planet then the planet must have been relatively massive and far from its star (see, e.g., Laughlin & Batygin 2017). Of course, other origin scenarios for interstellar objects exist, including some pretty cool and exotic ones (e.g., Cuk 2018; Seligman & Laughlin 2020). I'll just note that many of the broad characteristics of both 'Oumuamua and Borisov can be explained as planetesimals ejected from run-of-the-mill planetary systems (see Raymond et al 2018a,b).



8. Which fraction of known systems have as ordered (more than a few planets on circular orbits) a planetary system as ours?

SR: Thousands of exoplanets have been detected with a wide range in orbital architectures (for a review, see Winn & Fabrycky 2015). These range from systems with many close-in "super-Earths" and "mini-Neptunes", to "hot Jupiters", among other outcomes. Systems with many super-Earths detected in transit often have orbits that are extremely coplanar – much more coplanar than those in the Solar System.

There is enough data available to very roughly put the orbital architecture of our Solar System in broader context. The first step is to ask: if the Solar System were viewed by an alien civilization with present-day Earth technology, what planets would they find? The answer is: only Jupiter (with a decades-long radial velocity survey). No other Solar System planets would be detected. So, the search for other Solar Systems is, for now, the search for Sun-Jupiter systems. About 10% of Sun-like stars are orbited by a Jupiter-mass planet (e.g., Mayor et al 2011). About 10% of Jupiter-mass planets have wide, near-circular orbits like ours (e.g., Butler et al 2006; Udry & Santos 2007 – here, I used a cutoff for “Jupiter-like” orbits having semi-major axes wider than Mars’ orbit and eccentricities <10%). That puts the Solar System at the ~1% occurrence level among Sun-like stars.

This is a point that I often make in talks, and is explained in more detail in Raymond et al (2018) , as well as in this YouTube video: *https://youtu.be/dtwyb6eQJ9Q*.

9. Rapid Jupiter formation implies very different physical conditions in the disk (warmer and with snow lines at different radii than in older disks). How is that reflected in the models?

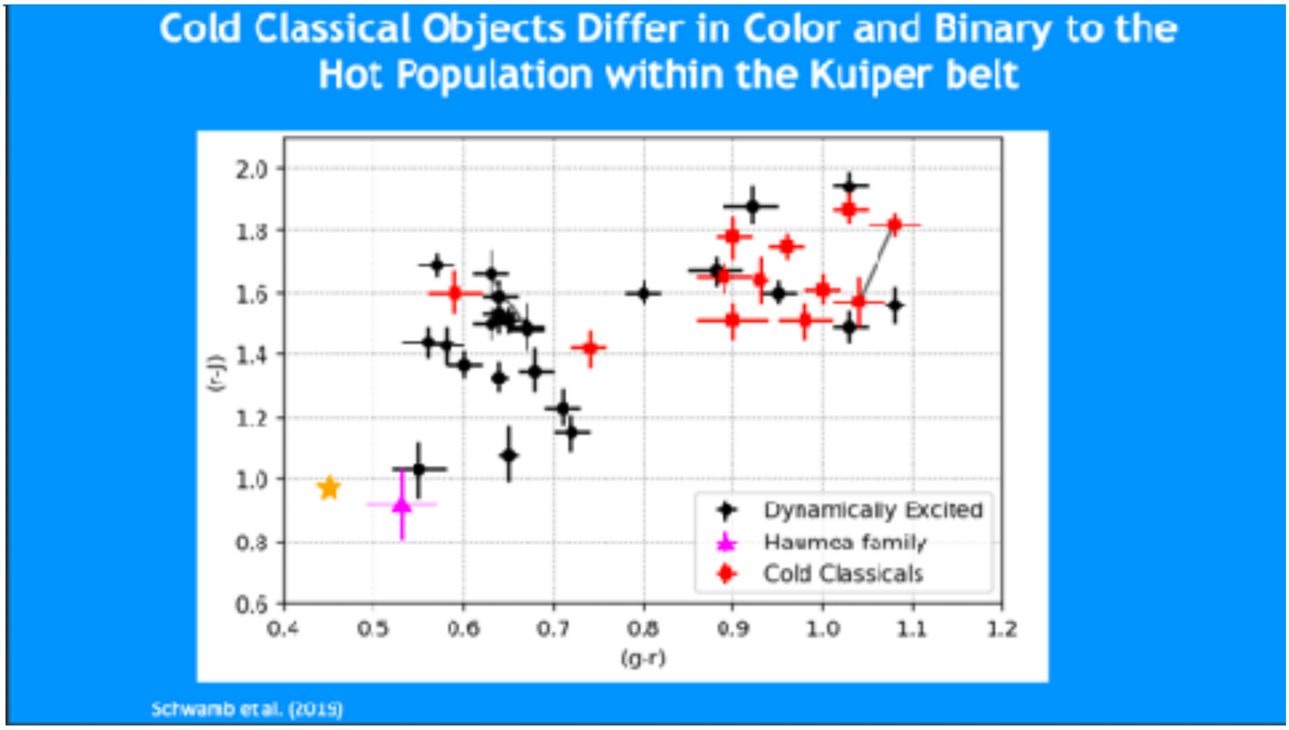
SR: There is plenty of debate regarding how, where, and how fast Jupiter and its core grew. Constraints include those from meteorites (e.g., the carbonaceous vs. non-carbonaceous isotopic dichotomy; see Kruijer et al 2017), numerical simulations, and disk observations and models. If Jupiter formed quickly then, indeed, it may have formed while the Sun’s planet-forming disk was relatively massive and therefore relatively hot. This is naturally accounted for in simulations, as the disk mass/temperature have a feedback on planetary growth and migration that is built in to the codes (e.g. the code of Bitsch et al 2019 accounts for disk evolution, migration and gas accretion in a close-to-self-consistent way).

10. Can Jupiter's composition be used to constrain its formation location in the disk and what is our current knowledge of it?

SR: The answer is: maybe. If we knew exactly what Jupiter was made of – its core in particular – then we could in principle deduce where it formed, as long as we had a good idea of the structure of the Sun’s planet-forming disk (see, e.g., Oberg & Wordsworth 2019, who performed this exercise). Historically, models have assumed that Jupiter and its core formed more or less

Arrokoth

Image Credit: NASA/JHUAPL/SwRI


Cold Classical Objects Differ in Color and Binary to the Hot Population within the Kuiper belt

Schwamb et al. (2019)

in-situ. However, new models span the full range of possibilities from Jupiter's core having originated in the outskirts of the Solar System (Bitsch et al 2015) to very close to the Sun (Raymond et al 2016).

11. How can that the cold objects can be so well separated in the *r-z* vs *g-r* colour-colour plane?

MS: Broadband colours can be thought of as obtaining really low-resolution spectra. *(g-r)* and *(r-z)* colours are telling us about the slope of the spectra. The cold classicals are likely separating because something near z-band is causing a change in slope/like a spectral absorption. What molecule or surface composition is exactly causing the absorption or change of slope isn't known yet. *New Horizons* Arrokoth encounter data may be able to shed more light on this. We'll likely need the next generation of telescopes, the 30-m generation, to learn more about the surface composition of the cold classicals in general.

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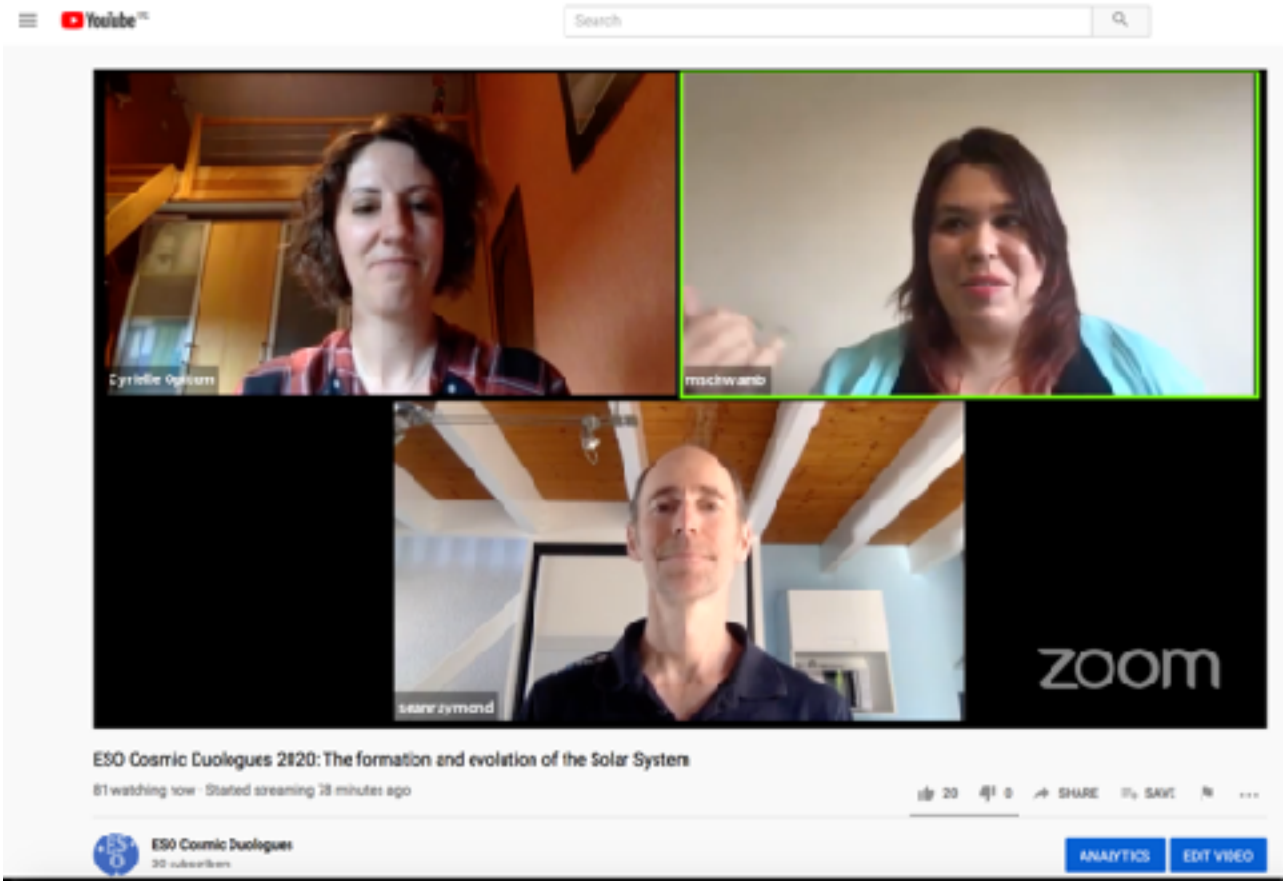

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