Photo Credit: ESO/P. Horálek

The atmospheres of Exoplanets

ESO Cosmic Duologue 7 - Interview

20 July 2020

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

On Monday 20 July, 2020, the seventh ESO Cosmic Duologue took place. It consisted in a discussion between *Neale Gibson* (School of Physics, Trinity College Dublin, Ireland) and *Jonathan Fortney* (University of California Santa Cruz, USA) and chaired by *Valentin Ivanov* (ESO), about the atmospheres of exoplanets. 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/duologue7.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.

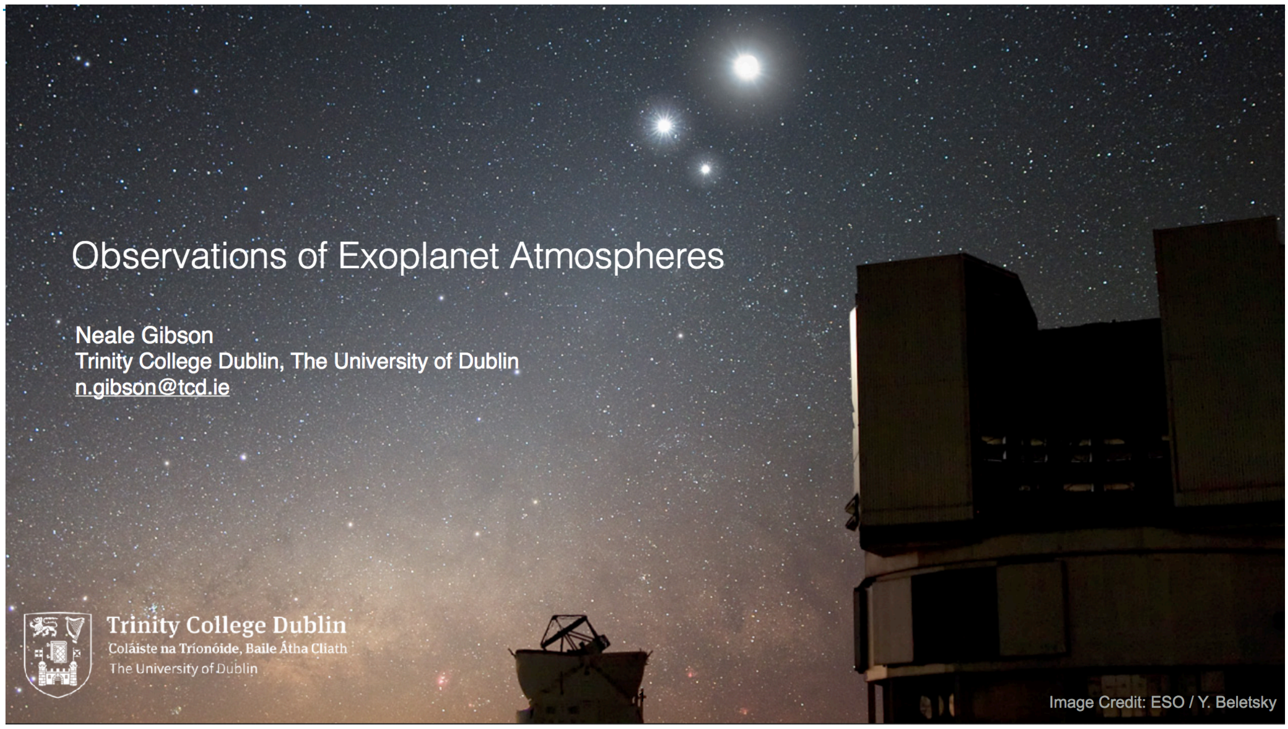
1. Which of the methods for obtaining data do you find most powerful and how do you decide you can trust the observations?

NG: There is no single method that is most powerful, as each has their own advantages and disadvantages. I work primarily with transiting planets, and in particular transmission spectroscopy. This uses the starlight that filters through the upper atmosphere of the planet, so in principle does not require us to detect either thermal emission or reflected light from the planet, which can be exceptionally hard particularly for cooler objects. However, transmission spectroscopy is very sensitive to even small amounts of aerosols in the atmosphere. Emission spectroscopy recovers light directly from the planet, which enables us to peer deeper into the atmosphere and obtain more information on the thermal structure. In addition, phase curves allow us to spatially resolve the emission. High-resolution time-series spectroscopy is also very effective at detecting atomic and molecular species, but it is proving difficult to extract quantitative information. Finally, imaging is the method of choice when we can spatially separate light from the star and planet (why would we want to be dominated by noise from the host star!). But of course, it can only access a small subset of planets for now.

JF: From the modeling perspective, I've seen that data quality can be high or low from any particular kind of observation. Of course, I don't want to spend my time thinking hard about a particular data set if it ends up not being trustworthy! I guess I've tried to develop my intuition about these things, and if I'm uncertain I'll ask a few different observers that I know well.

2. What is the biggest source of errors in the observations to obtain spectra?

NG: Instrumental systematics in the time-series observations are by far the biggest problem we face. This is the reason it took us many years from the first observations of an exoplanet atmosphere (2002) until we were finally able to take reliable, broadband spectra of even hot Jupiters (this point could still be reasonably disputed). The development of new data analysis techniques over the years, as well as new observational techniques (e.g. ground-based spectrophotometry, high spectral resolution time-series observations) has allowed us to check which instruments and methods are reliable. Cross-checking of results between groups is also on-going, with mixed results. Stellar activity is another huge problem, both for atmospheric studies and for measuring RVs. Again, repeated observations and new techniques are helping us cross-check results and techniques.



Observations of Exoplanet Atmospheres

Neale Gibson
Trinity College Dublin, The University of Dublin
n.gibson@tcd.ie

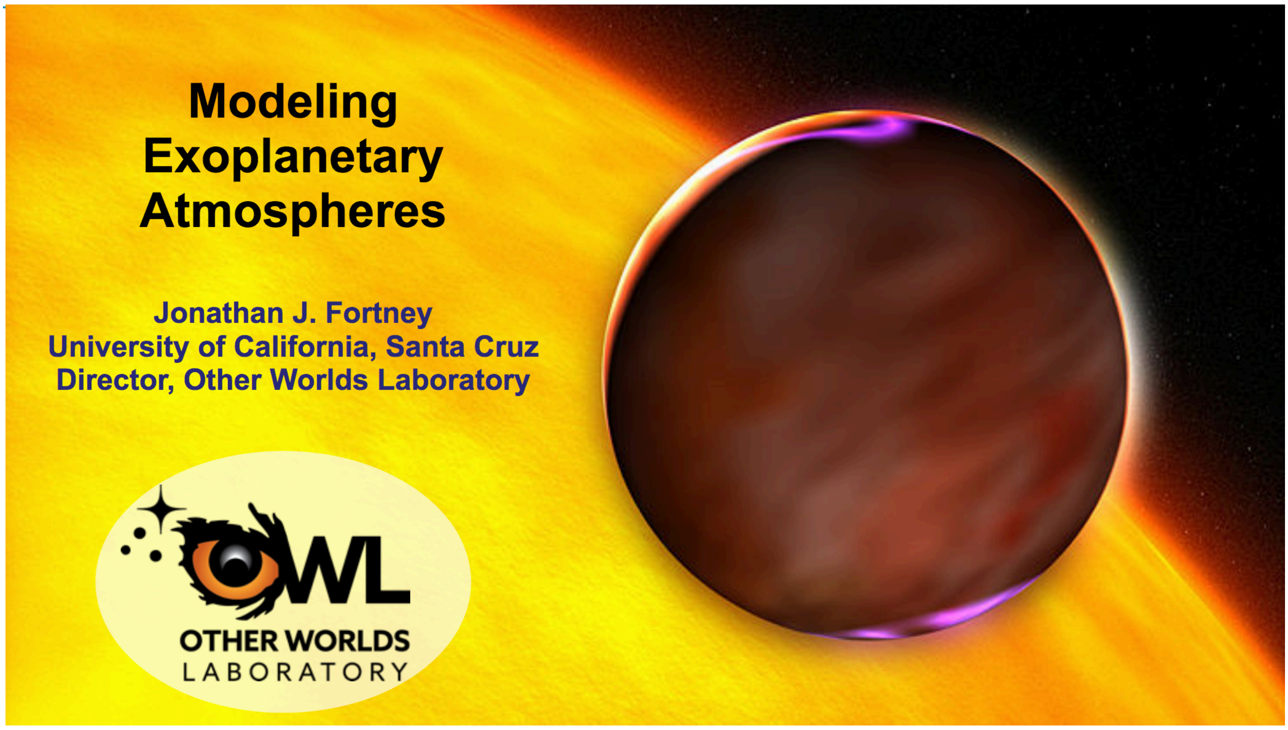
Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

Image Credit: ESO / Y. Beletsky

3. How does the studies of the exo-atmospheres help us to understand our own Solar system?

NG: The discovery of a vast population of planets very different from our own Solar System has certainly changed our view of planet formation, with the addition of migration and so on to explain the hot Jupiters. In terms of atmospheres, we someday hope to connect metallicities or abundance ratios of exoplanets to where they formed in their disk, and in turn to planet formation mechanisms, as Jonathan explained in his talk. Of course, in the long term — once we start looking at terrestrial planets — we can hope to also understand why some terrestrial habitable-zone planets end up like Venus, some like Earth, and some like Mars (or even something quite different) by linking their atmospheres to their surfaces and interiors. The statistical sample that we can potentially obtain from exoplanet atmosphere observations will clearly teach us a lot about planetary formation and evolution, and we hope to someday learn how rare or common are the conditions that enabled life to develop and flourish on Earth.

JF: One important aspect is that there are a variety of atoms and molecules, for instance in giant planet atmospheres, that we just cannot robustly detect in the solar system, given the very cold giant planet temperatures. We will probably never know the water vapor abundance in Saturn, Uranus, and Neptune, as water is locked into a cloud far below the visible atmosphere. What are the relative abundances of "rocks" and "ices" in the H/He envelopes in our giant planets? It is not clear that we'll ever know that. These are questions that we just cannot answer, but many of these "refractory" and "volatile" elements can be seen in close-in hot Jupiters and young self-luminous giant planets — they give us a fantastic opportunity to gauge the inventories of atoms and molecules in exoplanetary systems much better than we can in our own solar system.
For rocky planets, we see a tremendous dichotomy between the "twin" planets of Earth and Venus. Why is that? With a sample size of 2, it is hard to say — is the difference merely due to incident flux? From starting composition? From random happenstance? In the very long term, observing terrestrial planet atmospheres in other solar systems, across a large phase space of planet properties, will help us to understand the Earth/Venus question. That's just one example. But these are the types of questions where the exoplanet context entirely complements the more detailed solar system context.



Modeling
Exoplanetary
Atmospheres

Jonathan J. Fortney
University of California, Santa Cruz
Director, Other Worlds Laboratory

4. Does the observations follow theory, or the theory follows the observations?

NG: In some sense the theory is years ahead of the observations, in that modelling has largely been derived and tested using Solar System objects, including the Earth. But at the same time, planets show a remarkable diversity beyond what we anticipated, and the only way to truly understand this diversity will be to observe them. With regards to atmospheres, theoreticians were the first to point out the potential of using transiting planets to obtain spectroscopy, but even hot Jupiters — which are in principle the easiest to make predictions for as they should have similarities to stars/brown dwarfs of the same temperature — are still surprising us.

JF: There have been particular points at which theoretical ideas were extremely useful, and they drive the questions, but I think for the most part observations lead theory, as the planetary phase space, and planetary diversity, is just so large. It is true that we have a huge number and array of sophisticated models, but we need observations to tell us if we've actually been asking the right questions, up until now.

5. When doing predictions for future instruments, one will generally use the outcome of models and add some noise. How realistic is this?

NG: From an observational point of view, simply adding theoretical, Gaussian noise estimates is not realistic, as our observations for the most part are limited by instrumental systematics. These are essentially impossible to predict for future instruments, although we have good reason to expect much better performance than our current instrumentation. New instrumentation is expected to behave much better, and higher precision should enable us to model systematics with better accuracy. However, we'll have to wait to the first set of observations before we can assess the true capabilities of each instrument. I'll let Jonathan comment on the modelling aspect here.

JF: I think the thing to keep in mind is that the underlying model will probably not be "right." It won't have the mysterious new absorber that you'd only find from an observation! So, it is just fine to "noise up" models, 1D or 3D, but that is only a starting point.

6. Even the best transmission spectra have only a few resolution elements. But we use 3D models with a huge parameter space. How well is the problem constrained?

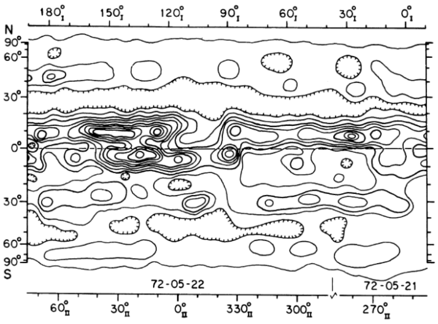
JF: I would say that transmission spectra have not been that powerful in constraining 3D atmospheric models. That is certainly true. The most robust constraints have come from secondary eclipse photometry and spectroscopy, where you are truly probing the thermal structure. Furthermore, phase curves probe the day/night contrast and the hot spot offset. In the JWST era, nearly every secondary eclipse spectrum will be made into an "eclipse map." That is the rare, but important case where we can learn about more than just a "hemispheric average," which is entirely typical of exoplanet observations. To be honest, I don't lose a ton of sleep over whether it is a constrained problem, or not. The constraints will always get better – it's a just a matter of if you're comfortable waiting a few years, (or a few decades?), or not. You do have to get comfortable with the notion that in many instances, though, you'll always be working with some kind of planet-wide average conditions. Again, there, any one planet may not end up being entirely "solved," but one may have to look at trends.

7. How good are the spectra of the planets in our Solar System that can be used to compare with observations of exoplanets? Is there an exoplanet that we have observed and modeled as well as, say, Jupiter?

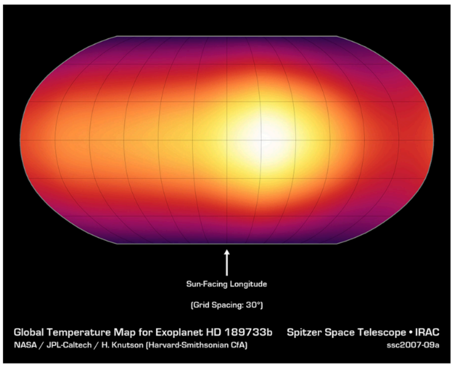
NG: There are of course direct spectra of Solar System planets that can be compared to emission and reflection spectra of exoplanets. A potential problem is that the Solar System spectra are spatially resolved, which may make direct comparison difficult. I know this has proved problematic when trying to get disk-integrated spectra of the Sun when studying the effects of activity on stellar radial velocities, for example. There have also been measurements of transmission spectra of the Earth taken using reflected light from the Moon during lunar eclipses.

JF: We are still some decades behind the solar system, probably 50 years, in terms of data quality. Spectra from the late 1960s and early 1970s, for the solar system, are similar to what we are getting for exoplanets today. Many of the modeling tools used have been validated in some ways against solar system planetary observations. But to be frank, we are often typically using stripped down versions of these tools, given that the data quality is so much lower. It is true that 1-to-1 comparisons can be difficult, as it is difficult and rare to get planet-wide average spectra in the Solar System, rather than spatially resolved. If you think about it, this will probably fundamentally limit our ability to understand exoplanets, if we never reach the spatially resolved point of view.

Infrared Brightness Maps in Thermal Emission

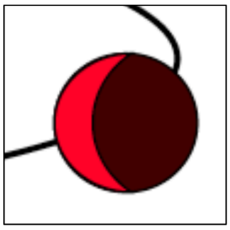


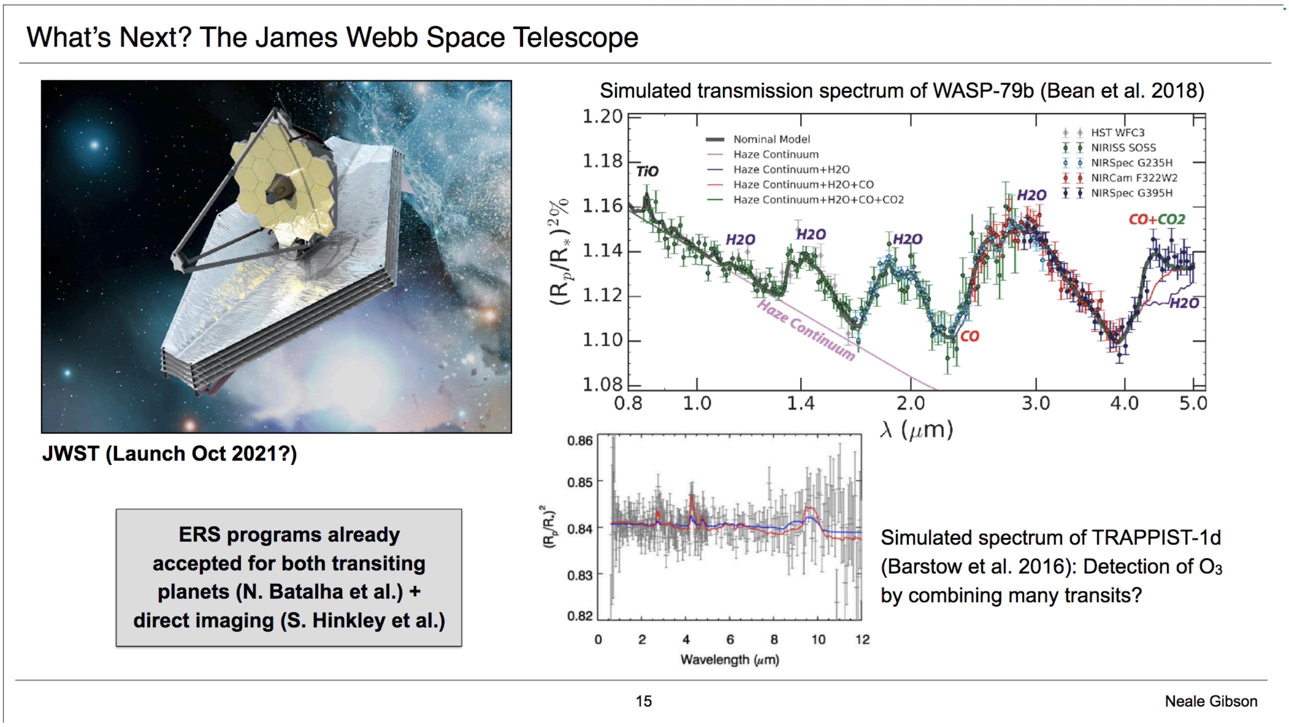
- Jupiter, 1972
Key et al., 5 μm



Global Temperature Map for Exoplanet HD 189733b Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / H. Knutson (Harvard-Smithsonian CfA) ssc2007-09a

- HD 189733b, 2007
Knutson et al., 8 μm





What's Next? The James Webb Space Telescope

JWST (Launch Oct 2021?)

ERS programs already accepted for both transiting planets (N. Batalha et al.) + direct imaging (S. Hinkley et al.)

Simulated transmission spectrum of WASP-79b (Bean et al. 2018)

Simulated spectrum of TRAPPIST-1d (Barstow et al. 2016): Detection of O_3 by combining many transits?

15

Neale Gibson

8. Can you name the greatest discoveries in this field in the next 5, 10 and 20 years? What is the future of exoplanet atmosphere studies?

NG: I think one great discovery all of us are looking forward to is for the first spectra of habitable-zone Earth like planets and searching for biomarkers. Whether that happens in the next 5, 10, or 20+ years, I really don't know! The M-dwarf opportunity will enable a "shortcut" to looking at Earth-like exoplanets, and will be possible with JWST and the ELT for a handful of objects. But whether these planets can maintain their atmospheres is still an open question. Beyond that, large space-based telescopes will likely be required to enable direct imaging of such objects around more massive stars, and plans are being made for facilities to be launched in the 2030s. I think in the near future we can look forward both to very detailed studies of gas giants, studying their atmospheres, formation and evolution in detail, as well as simply trying everything we can to extract any atmospheric information about terrestrial systems. Statistical studies of exoplanet atmospheres will play an increasingly important role, once we've mastered new instrumentation and techniques.

JF: In 5 years we'll have exceptionally well characterized high S/N spectra for many Jupiter- and Neptune-class exoplanets from JWST. We will be able to validate 2 decades of modeling in an entirely new and robust way. We can begin to realistically think about trying to understand the atmospheres of these classes of astrophysical objects, for the first time. In 10 years, we will have searched the atmospheres of at least 4 (perhaps more!) of the TRAPPIST-1 planetary systems for signs of life, and we will have (I think, probably crude) constraints on their atmospheric composition. That will also come from JWST. In 20 years, things might look similar to the 10-year question, although by then a statistical assessment of a wider range of objects will begin to take center stage. The atmospheres of Earth-like planets around Sun-like stars is probably beyond the 20-year horizon.

9. How many exoplanets will we be able observe by transmission spectroscopy on one hand (from the ground or with JWST), and by combining direct imaging and high-resolution spectroscopy with ELT or with other telescopes? What is going to be the most useful?

NG: This is really dependent on the science case. As noted earlier, each of the different methods will provide different information. We can expect spectacular results from both JWST and the ELT.

JWST will excel at stable time-series observations particularly for close in objects, and the ELT will obviously have higher spatial and spectral resolution, opening up possibilities to directly image nearby planetary systems perhaps even in the habitable zone. The best method for terrestrial planets will likely depend on whether the M-dwarf planets in the habitable zone can maintain their atmospheres, and gas/ice giants will be studied with a combination of techniques.

JF: Within a decade, I could imagine spectra of ~100 transiting planets from JWST. ARIEL aims for spectra of 1000 transiting planets. The ELTs will increase the number of imaged planets, to dozens of planets with atmospheric spectroscopy, after a large number of longer-period planets are found from Gaia, in addition to continuing RV surveys.

10. Given high enough Signal-to-Noise high resolution spectra taken for transmission spectroscopy, do you think it will be feasible to take a retrieval approach to getting abundances?

NG: For now, retrievals from high-resolution spectroscopy are mainly limited by the statistical techniques and computational power, not the SNR of the observations. There have been some recent works already trying to solve this problem (e.g. Brogi, M. & Line, M.R. 2019, AJ 157, 114). Fitting spectra directly to high-resolution data is certainly possible, requires detailed computations to produce high-resolution modelling, and a lot of computational power to then Doppler shift the models and fit directly to the data — which in the case of high-resolution time-series data can contain many millions of data points. The remaining difficulty is that we have to filter out the stellar spectra, and this procedure naturally affects the exoplanet spectrum too. This means that we also have to modify the exoplanet models in a complex and computationally expensive way. But I think this is a problem we can solve in the near term.

JF: People are tricky and smart. I think that we'll get there.

11. What about clouds? Is there a way to penetrate through them?

NG: Clouds are problematic for low-resolution transmission spectroscopy, particularly at optical and NIR wavelengths. There are a few options. One is to use emission spectroscopy that has more favourable geometry and is less sensitive to clouds (this is also the case for directly imaged planets). This is not always possible of course and requires us to access thermal emission or reflected light from the planet. But not all is lost for transmission spectra. JWST will help with its longer wavelength coverage. Not only will this access a region where clouds are less of an issue, but it may also help us access spectral features from cloud/haze particles to understand their nature. And of course, the more we understand clouds, the more we are able to target planets where we expect clear atmospheres. For example, the (ultra-) hot Jupiters may be more amenable to detailed abundance measurements than their cooler counterparts. Finally, spectral resolution also helps, as spectral lines extend higher in the atmosphere at high-resolution, and therefore we can probe the atmosphere above the cloud deck.

JF: I think we have to also think of the cloud "opportunity." If we are able to understand the cloud distribution in latitude/longitude/depth space, from a variety of observations, then we will learn a lot about condensation, advection, and atmospheric transport in these atmospheres. Yes, clouds will obscure molecular abundance features. But because clouds are not going to be well-mixed, we should think more creatively how to use clouds to gain a better understanding of atmospheres, in 3D.

12. What role do you expect polarimetry to play?

NG: Polarimetry is a technique that is still considered somewhat niche in the study of exoplanets, and so far, we are missing a major result demonstrating its use. There have a been a few studies that have tried to detect optical phase curves (i.e. reflected light) of exoplanets by using polarimetry to filter out the stellar light. But these studies (as far as I'm aware) are still disputed. I suspect because there is limited instrumentation to perform high precision, time-series polarimetry, as well as few bright-enough targets. For direct imaging, I know VLT's SPHERE has a polarimetry mode, but I'm unsure how effective it has proved in detecting planets so far. Possibly polarimetry will play an important role in the future, once we can routinely detect reflected light from planets.

JF: This has come up every year or two for many years. It's still just hard to say, which is not a satisfying answer. My own point of view is that polarimetry has played a fairly limited role in probing Solar System atmospheres, generally, aside from great success of probing the composition of Venus's clouds. So, it has never been clear to me which "side" exoplanets will fall into on that question, the little success side, or the huge discovery side. I think that it is important that people keep developing the observational and theoretical tools. That is certainly still happening (albeit slowly).

13. Does improved time resolution help (for example, using NIR electron avalanche photo diode arrays)?

NG: There are not many cases I can think of where we are limited by time-resolution — perhaps some transit surveys, but that's typically an issue with data volume rather than hardware. Typically, a few minutes cadence is required to sufficiently resolve the transit and/or velocity shift of the planet. Speeding up readout times would have a modest impact on the efficiency of observations. However, improving the stability of NIR detectors would be a major improvement for exoplanet science.

ESO Cosmic Duologues 2020: The atmospheres of Exoplanets