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| Tiffany Kataria: | ... So the notification. There we go. All right. Good afternoon, everyone. My name is Tiffany Kataria. And I'm the steering committee chair for the Exoplanet Explorers Science Series. So thank you for attending our fourth set of presentations. We're almost done. We're nearing the homestretch. It's flown by, it's been really exciting. So just a preamble for those that aren't aware of the program. The Exoplanet Explorers are ExoExplorer Science Series is sponsored by the ExoPAG Executive Committee and NASA's Exoplanet Exploration Program. So thank you for your support. And this program aims to enable the professional development of a cohort of graduate students and our postdocs in this case, both in exoplanet research, other dubbed ExoExplorers. Each member of the cohort will be featured in a webinar like this one that will be live streamed to the exoplanet community, helping to increase their visibility in the field, which is especially important now, when we're meeting virtually. |
|  | The cohort will also learn from the experiences of established exoplanet researchers in the field that we've dubbed exo guides, via a combination of tailored presentations and small group discussions. And this first cohort is currently running from January at the beginning of this year through to June, the next month. And it's comprised of 10 excellent early career scientists. So if you want to learn more information about the program, the Organizing Committee Chair, Vanessa Bailey, should have pasted some information in the chat and feel free to reach out to us with any questions. So it's my pleasure today to introduce our two speakers. But before I do that, I just want to set a couple of ground rules or reminders to behave professionally and with decorum in this forum. And second, we plan to save questions until the end. So please either use the WebEx chat tool, which we'll take a look at or use the hand raised tool, which for those who are not as familiar with WebEx. |
|  | If you hover over your name, you should see a little high five icon, you can click that and that will indicate that you're asking a question, and we'll call on you. Okay, and with that, let's get started. So our first speaker today is Jules Fowler. Jules Fowler was an undergraduate at Tufts University where they received [inaudible] after system philosophy, in 2016. They then worked as an analyst and software engineer for the Space Telescope Science Institute, as part of the Russell B. Makidon Optics Laboratory. Currently, they are first year graduate students at UC Santa Cruz and an NSF Graduate Research Fellow. They are also a member of the AAS Committee for Sexual and Gender Minorities in Astronomy or SGMA. And their talk today is entitled, Don't Heckle My Speckle: A Coronagraph Design Study for the SEAL testbed. Always a mouthful sometimes. Alright, Jules, whenever you're ready, go ahead, share your screen and get started. |
| Jules Fowler: | All right, let me set this up. And all right, I think that looks good for everyone. First and foremost, I want to say thank you all so much for giving me a little bit of your time today. I'm really excited to talk to you about the research that I've been working on. I want to tell you about exoplanets and more specifically, the instrumentation that we use to better understand and characterize them. And I'm going to be walking you through a design study I've been doing for a coronagraph for the SEAL, or the Santa Cruz Extreme Adaptive optics Laboratory testbed. So the name of my talk is Don't Heckle My Speckle: A Coronagraph Design Study for the SEAL testbed. And I've named it like this, because in particular, I'm a sucker for a quippy one liner. But I also over the past few months, as I've been working on this have been really enjoying coming to love, hate and be super confused by in general the speckle. So I want you all to feel this way about the speckle after this talk is done. |
|  | And if speckle isn't super meaningful to you, right now, I want to make sure that you know that I'm talking about speckles of light that come from exoplanet observations and the rest you will get a much better understanding of as I go through this talk. So first, I want to give you a quick outline of what I'm going to talk about today, I want to motivate extreme adaptive optics for you. I'm going to go through the SEAL testbed, I want to give you a quick optics refresher in case it's been a while since you've thought about some of the optical things I'm going to go through. I want to give you a primer on coronagraphy and some of the coronagraph design stuff you might not have on hand. And then I'll start going through my simulation to coronagraphs for our testbed. Finally, I'll look at the current state of the coronagraph design that I've been working on and talk about some next steps for this work. |
|  | So first, I want to talk to you about direct imaging and extreme adaptive optics. So I'd be remiss if I didn't put the one go-to plot of Exoplanet Survey demographics. And in particular, what I want you to notice when you look at this plot is that over the past 20 years, we have discovered so many exciting and fascinating exoplanets, but we have not directly imaged very many of them. And what I mean by direct imaging is particularly that we can spatially resolve the light of the planet from the light of the star. So we can individually see a planet, as opposed to the bright central star, which can be quite difficult because we will need to extinguish the light from a very, very bright central source and create high contrast in our image, in order to be able to bring up this planetary light, as opposed to other very excellent and popular methods like noticing the dip in light like transits or noticing wiggles in our radial velocity curves. |
|  | And in particular, I like to use the example of HR8799, which is a famous beautiful planetary systems that we were able to directly image in the infrared. Direct imaging can be really exciting because it can unlock the ability to better characterize exoplanets. We can take really great transit, or sorry, we can take really great spectroscopy when we directly image. And well, I don't want to knock the transiting spectroscopy folks, they're also doing some really amazing work. With direct imaging, we can access spectroscopy, where planets may not be transiting in front of stars. And we also don't take the photon hit because we can directly image the planet itself instead of having to directly image the difference between the stellar source. So in order to do this, we've been using mostly ground based imaging and ground based telescopes. Well, we think this would be an amazing case for space, you see a ton of issues that with stability of telescopes, we can't get mirror that big up there. And also just issues with optics and that we see a lot of issues with light, which becomes speckles. |
|  | So instead, we're doing this from the ground. And that means that we need to use adaptive optics. And so here I have a diagram of an adaptive optics system. What happens is that as light, which will have a shape, we call a wavefront moves through the Earth's atmosphere, it'll be distorted by atmosphere, different pockets of different sizes will break up the shape of the wavefront. And we will be able to carefully and beautifully resolve our images when they make it to the ground. So what we do is we sense the shape of that wavefront with a wavefront sensor, we calculate a correction in order to better look at our image and we apply that correction with an adaptive mirror, also called a deformable mirror. And we're doing that usually with little pokes in the back that we call actuators. And these actuators can characterize how well we apply corrections. I'll talk a little bit about that later. And if you want to concretize this, this is a beautiful image of Neptune with and without adaptive optics. |
|  | So you can see that it gets really befuddled by the Earth's atmosphere. And then when you turn it on, we get this really crisp, beautiful image. But then when we look at exoplanet observations, we find that the Earth's atmosphere will create speckles of light, light from the star will be aberrated into this really dramatic pattern that also moves in real time. So it's a very challenging problem to try to get rid of enough light to be better to dig out the stark area where we might be able to see a planet. And this is a better example of an active adaptive optics correction. What we're looking at here is light as it comes through the Earth's atmosphere, then we're looking at how we would apply a correction to one of our deformable mirrors. And then the final image both how we sense the wavefront, and this beautiful, clean PSF, where suddenly, maybe we couldn't see a planet after all. And this is what I'll be referring to when I use extreme adaptive optics. |
|  | And now that I'm more motivated, what these images look like, I want you to look at a speckle of light. And I want you to look at a planetary observation. This is HD 95086b, which when it was discovered, or when it was imaged in 2013 was one of the faintest directly image planets of note. And I want you to think about the kind of work that we're doing here, trying to make sure that we can extinguish enough of these speckles, so that we can see enough of these planets. So now I want to tell you where the Santa Cruz Extreme AO Laboratory or SEAL fits into all of this. So in particular SEAL is trying to test novel wavefront sensing, wavefront control and coronagraphy and synergy with the W. M. Keck Observatory. Our plan is to use very similar computers and very similar software, we're actually using the same software, in order to be able to develop experiments and technology that will be able to seamlessly integrate back into Keck, as well as acts as a testbed for Keck as their daytime testing gets completely overloaded. |
|  | And there's a lot of really exciting work going on here. I wish I had enough time to talk about it today. But today, I'll be walking you through the coronagraph design that I've been working on for the testbed. I want to quickly go through some of the parts of the testbed that will impact design choices that I've been making. So in particular, we have this area here where we can simulate atmospheric turbulence, both with plates that will apply a phase two and then be able to move as well as a spatial light modulator, which uses liquid crystals to be able to play turbulence patterns that we can add to our testbed. We also have an area where, not in our first iteration, but in later iterations, will be able to integrate elements that will let us better simulate the Keck's pupil. We also have two deformable mirrors here. We have a low and a high order deformable mirror. And then we also have the coronagraph, which is what I've been working on. |
|  | So now I quickly want to go through some optics that might be a few years old for you just in case. So when I look at light throughout the rest of this talk, I'll often give you a look at the focal plane and the pupil plane. The focal plane is probably what you're very familiar with, what you think of as an intuitive image. This is the plane where things are in focus, focuses is to a point and this is the image plane that we often talk about in our system, which will be in arcseconds or degrees. This is one handy Fourier transform wave from the pupil plane, which is a track of our system aperture. And we'll think about this in terms of x, y. But also, instead of looking at our focal plane in degrees, I'd like to look at it in natural units, which is λ/D, by which I mean lambda or the wavelength of light coming into our system for our telescope or for our testbed, we're looking at 633 nanometers, which is visible light, over the system diameter, which, for a typical telescope, this might be the primary mirror diameter. |
|  | And this will set the diffraction limit of our system and will also apply to area rings as they pop up. So it'll be a useful way to track the focal plane images in our system. I want to give you some very quick coronagraphy basics, just so the things that I'm talking about make sense to you as I go through them. So if we think about starlight and how we want to suppress it, in order to be able to observe a planetary companion, first, we'd want to throw in what we call a focal plane mask, which is a mapping element that we'll put in the focal plane of our system. And one of the simplest versions of this would just be an opaque spot. Once we do this will extinguish sunlight, but still not quite enough to make out the planet. So instead, or sorry I should say as well, we add a Lyot Stop, which is a water-like element named after Bernard Lyot, the inventor of the coronagraph, that allows us to finally block out enough light to be able to make out this planetary signal. |
|  | And what does this look like if we look at images? Well, if we take the focal and pupil plane images going through that same path, here, we start with an image that has both a star and a planet. So I encourage you to squint at the screen and try to figure out where the planet is before the coronagraph goes in. Once we add in the focal plane, you can see that we've masked out light from the center and this focal or sorry, once we add a mask at the focal plane, and then look at the focal plane image, you can see that we've masked out a lot of light from the center of the source. And this is even more interesting in the pupil plane. Because you can see that here, all of the light that was originally in the system has been diffracted around the edges. And that's why we still see this very bright pattern that makes it impossible to make out our planet. And then once you put in the Lyot Stop, voila, the planet appears. And this is not that I've moved the image, this is a planetary source. |
|  | Remember before there was this bright star here, and now all we can see is the planet. And you can see here in the pupil plane that by adding a Lyot Stop that was a ring that went around these edges, we were able to block out almost all of that light. And I will say we weren't able to block out the light completely. This is matching the scale to the prior images so you could get an idea of how much light we were losing in our system. And this is some of the leftover light artifacts that we couldn't quite kill with our coronagraph. And in particular today, I'll be talking about two different kinds of coronagraphic masks, which are a focal plane. Sorry, a Classic Lyot and a Vortex coronagraph. A Classis Lyot is the example that I walked you through in that little demo. It's what we think about as an opaque spot where we just block light. And this has some advantages as far as a coronagraph. It's very simple to integrate and align. |
|  | What you see is very much what you get and it doesn't... It isn't too highly impacted by other sources of error and systematic issues that we'd see when we integrate a testbed or a telescope. However, this spot has a physical size and that means that if we have to make this spot say three or four λ/D, that means that we will be able to image a companion that's three or four λ/D away from our central star. On the other side, we have a vortex coronagraph and a vortex coronagraph on paper has practically unparalleled light suppression. However, we see with the vortex that we are unable or we see what the vortex that we are much more impacted by wavefront error and other sources of error from our testbed and so we can really see the performance degrade and I'll show you that in detail shortly. I think a vortex can be kind of hard to wrap your head around when you think about the shape of the mask. |
|  | It's this sort of spiral ramp structure and it's also has a charge which determines how many of these spiral ramps you see but a comparison I quite like is that of Halley's marble league. I don't know if anyone else got into the MarbulaOne racing this summer. So think about this as M. C. Escher's marble funnel. And in particular, we'll need some sort of metric to be able to understand how well our coronagraphs are performing as we work through this. And for that I'm using a contrast curve that I've normalized by the throughput of the planetary companion. So this is laid out very well in a paper by Jensen-Clem from 2018. But if we think about injecting a planetary companion at various λ/D, we can then look at the contrast that our system might have. Which is to say that here, we'd be able to observe a planetary companion that was around 10 to the 5.5 times as faint as the star that it orbited. |
|  | And for reference, this is a no coronagraph system. So this is just how light would look as you imaged it, but this is for a perfect case. So this is no atmosphere in a vacuum or optics are 100% perfect. This is not what we'd actually see an image performance. And then I've over plotted this with some interesting realms of note. So your average gas giant would be about 10 to the six times thinner than a stellar companion. So we need contrast in this region. And your average rocky planet would be 10 to 10 times thinner than a star. So you'd need contrast in this region. And I want to say that as I show you contrast curves, I do not expect this to be the final, "Don't argue with me" contrast performance of the coronagraph, I'm just using these as a baseline to be able to compare various designs and various error as it propagates through the system. |
|  | So that being said, let me show you what I've been working on and the simulations of coronagraphs I've been making with HCIPy. So HCIPy is a high contrast imaging package for Python. It's a really great framework to incorporate everything from a deformable mirror to a coronagraph design into your work. And I want to mention before I go into the specifics of my simulations that I mentioned that we're trying to use a Keck-like aperture in the future but the first phase of our testbed is just a simple circular aperture. And so I use simple circular apertures for all of my work and these simulations moving forward. What you find when you start looking at the literature and seeing how the simulations pop up, is that you can on paper, for an idealistic system design and what I call a B- Lyot coronagraph. And what we see is that if we get a Lyot Stop that's undersized with some respects to the system aperture. |
|  | So by point .67 here, I mean that 33% of the light from around the edges of the system are being blocked by the Lyot Stop, we'll see that only some of these contrast curves are just barely able to beat the no coronagraph case. And then if we look at a vortex coronagraph, we see that on paper for an idealistic system, a vortex performs shockingly well and it honestly doesn't seem to make a ton of impact in this small regime, what they'll use up is. Past a certain threshold, before we throw away too much light from the edges of our system, we're able to see really great performance from our vortex. But unfortunately, we are not perfect people, we do not have perfect optics and we have very bad atmosphere. So, when we look at actual imperfections and actual cases for our testbed, we see something very different. So one of the first things that I'm going to incorporate into my simulations is wavefront error. |
|  | If we think about imperfect optics, subtle issues in the machining of the optics can introduce phase errors. Where we'll see little bits of deconstructive interference in our light and create speckles once again. So one example of what we see is high order wavefront error from our optics. I've exaggerated these left most plots to give you an idea of what these look like. So this is some dramatic speckly high order wavefront error. Here, I have some more subtle, but still unfortunate warping that we'd see for lower order wavefront error. And then off to the right here I have an example of what this might look like for one object on our testbed. This is the aberrations in the optic that we would expect, given what we'll be able to machine our optics to in that given precision. And you might not see a ton of aberration here by eye. But when we look at how that moves through into the contrast curve, it's kind of shocking, frankly. So if you look at the no coronagraph case, we can see that our optics introduces a little bit of error. |
|  | It's pretty hard to tell it apart from the no error case. When we look at the Lyot again, you can start to see a subtle difference from the wavefront error and no wavefront error case. But where we really see it is the vortex. The thing to know about a vortex mess is that a vortex is actually interfering the light of the start with itself. So when we add wavefront error to the system, the vortex performance drops adequately reduces. And one thing to note is that there actually is a way to get really good performance out of a vortex even when you include wavefront error. And that's to crank up the charge very high. But unfortunately, as you increase the charge of the vortex coronagraph, you also lose the ability to image these closing companions. And that's what we can kind of see here. So this green line is our charge to vortex without any wavefront error. This green dashed line is how the contrast degrades when you add that wavefront error, and then this black dashed line is a very high charge vortex in order to recover that contrast. |
|  | And then I also want to look at what this looks like for the coronagraphic PSF. So remember, before, with a vortex coronagraph, we could get this beautiful little planet source just popping out. And if we include wavefront error into our simulations, realistically for an error from an optic on our testbed, we'll see a ton of light that comes back into the system, especially from the center of the PSF. And another thing that we have to think about is that a typical vortex mask is an imperfect machined optic itself. So it's very hard to create this dimple here. And so instead, what's very common when you look at practical machining for these, is that there will be an opaque spot over that center. And this is as if we have a Lyot coronagraph as well as the vortex coronagraph. And this also has a major impact on our simulations and on our performance. So again, we have the perfect vortex coronagraph. And the final coronographic PSF for the vortex with this thought, also introduces a ton of excess light and error that we'd be unable to appropriately correct for with just this coronagraph. |
|  | And how that propagates into our contrast groups, we can see here that the vortex coronagraph with no spots is again, down here in this region. And then we lose almost two orders of magnitude of contrast when we include that spot in our simulations. And then we are an adaptive optics testbed. So I would be remiss if I didn't talk about the atmosphere, and how we'd be able to correct that with our adaptive optics system. So here, I'm showing you the phase that we would impart with different atmosphere models. And here, this is just the atmosphere if we didn't control it at all. This is like the picture I showed of Neptune at the very beginning pre-adaptive optics. It's just this big clouds that we can't really penetrate. And this is up to about two pi assays that we could impart. If we had a 50 actuator system, we can already do a lot better here. You can see that we've broken up this big chunk of phase into these smaller structures. And then we have a kilo dm, which is the deformable mirror that has about 1000 actuators. |
|  | And with that, we'll be able to control the phase down to much more fine resolution. And if you can't see anything here, that's because I wanted to match the contrast for these three images. But I've also rescaled these to the maximum so you can kind of get an idea of the better structure here. And we can see that with the deformable mirror we'll be using on our testbed, we'll be able to control down to these very fine structures. And we'll only be parting about pi over six of phase error, as opposed to this big, ugly two pi worth of phase if we weren't controlling it at all. And we didn't find that this really impacted the contrast performance to a visible level at all, when we ran these simulations. So that being said, with our last few minutes, I want to talk about the current state of the coronagraph design. So looking at the Lyot, we found that it was best to crank up the focal plane mask as high as possible without risking the ability to see planetary companions that we'd be hoping to view. |
|  | So we set our focal plane mask at 3λ/D. So, over them 3λ/D on, we'd be able to see companions in this area. And then the issue with incorporating a Lyot Stop is that like I mentioned, the diffraction limit of our system is set by the size of the Lyot Stop. So as we make the Lyot Stop smaller and smaller, we throw out planetary light and we also increase the system resolution. Or we decrease the system resolution we make a larger object with, a larger PSF we'd have to be limited to. And that being said, we found that the best design for here was going to be a Lyot Stop that was 0.6 relative to the primary telescope aperture, with a 3λ/D focal plane mask. |
|  | And here's an example of the final coronagraphic PSF that we might expect. You can just barely still make up a planetary companion with a lot of light still in our systems. And again, we don't expect this to be our heart and true contrast. But this would map to about 10 to the -7 contrast with our companion that we've injected at 8λ/D. Similarly for the vortex we would see that well, .98 actually held up as the largest Lyot Stop that we could do and still get great performance. That is quite difficult to align when it comes to practically thinking about integrating a testbed. So instead, we think about using a Lyot Stop of about .9. Because again, it had very similar performance. But once you've incorporated our wavefront error and other sources of error in the testbed that unfortunately I didn't get to talk about in these few minutes. You can see that we really lost a ton of contrast. |
|  | This only barely if at all underperforms the Lyot Stop at this point even though when we looked at those on paper and in an idealized system, the vortex had such much better performance. And so the answer for this is that we'll want to make our coronagraphs more interesting and more complex. And in particular, I got the amazing opportunity last week to meet with a new collaborator, Gary Wayne, who is at JPL with you all. And he gave me a new performance metric that I'm going to incorporate and I didn't have time to throw this in before this talk. But that will be part of my next work is that I want to incorporate this new performance metric, looking at a cost function on exposure time. Like I mentioned, I'll want to design and model additional elements that would crank our contrast down even further, including an appetizing phase pattern that we'd be able to apply with deformable mirrors. And also, like I mentioned, we're hoping to throw in future tech-like structures so that we can better match the Keck Observatory. |
|  | We might use some of this work to design and simulate preliminary designs for the 30 meter telescope. And we're also going to use this testbed this summer to be doing some wavefront control... or some predictive wavefront control comparisons side by side. I want to very briefly say that there are so many people I'd love to thank. The ExoExplorers program for giving me the chance to talk. The UCSC lab for Adaptive Optics and particularly my advisor and my research group. And also Anand Sivaramakrishnan and Gary Ruane for giving me some really helpful coronography advice since I've been working on this project. And then finally, I'll leave it at my conclusion. And please, if you want to contact me after this, feel free to and I'll open it now for any further questions or heckling. |
| Tiffany Kataria: | Thank you Fowler. I don't imagine there'll be any sort of heckling. I see a lot of applauses, which I hope you see too. Given the time, let's say we have time for maybe one or two quick questions. Again, please use the chat or the hand raised tool if you have questions. I see a question from Doug. Doug, go ahead. |
| Doug: | Hi Jules, great talk. So I have a question. I noticed you showed a number of plots of contrast versus λ/D. One of the things that I noticed that look different, and of course, I typically look at contrast curves from vacuum systems, and for space based coronagraphs and stuff like that. And it appears to me that the fall off, the drop, drop... The increase in contrast, of the inner working angle that some of these space based simulations is more dramatic than what you see in the flow. There you go. The slope of the curve as you go from the inner working angles to larger λ/D seems to be more gradual in these simulations then what I'm typically familiar with. But simulations of space based coronagraphs or things from the HCIT or something like that at JPL. Is that a consequence of, working in air as opposed to working under vacuums sort of faceplate conditions? Or is it just that there's no difference and it's just, I'm trying to compare apples to oranges in different products? |
| Jules Fowler: | One thing that I might ask is, I know a lot of times it's really common to show raw contrast as opposed to contrast that's normalized by throughput. So, I'm not sure if you're thinking of contrast curves that involve raw contrast of the image plane or also normalized by throughput that can make a big difference. |
| Doug: | Okay. All right. I [crosstalk]. |
| Jules Fowler: | Otherwise, I'll say that I did not actually simulate in-air versus in-vacuum. What I meant by in-vacuum versus otherwise is whether or not we're considering phase errors that are introduced by Earth's atmosphere and how that's controlled by an AO system. So my apologies if I was playing fast and loose with the term vacuum. |
| Doug: | Oh no, no. It's fine. It's fine. It's just, it's very interesting stuff. And you're right. I mean, I was trying to think of how... Because you're talking about Lyot coronograph here and of course, it's going to be a Lyot coronagraph on the Romans Space Telescope too. And so I'm just, I am not a specialist in optics. So, I sort of scratch my head and try and make sense of the glass and stuff like that. [inaudible] say... But thank you, I appreciate it. Again, very good talk. Good, very interesting. Good work. |