<u>Background and Motivation:</u> Exoplanet direct imaging is made extraordinarily challenging by the extreme starlight suppression required to image faint planets around brilliant stars. The noise-limited performance of current high-contrast imaging instruments can resolve planets up to 10 million times dimmer than their host star. In order to access Earth-like planets – the highest-priority planetary targets named by the Astronomy and Astrophysics Decadal Survey [1] – sensitivity must be expanded to planets 10 *billion* times fainter than their star. The primary limitation on increasing contrast is speckle noise, which is scattering of the stellar point spread function (PSF) that can mimic or obscure planet signals [2]. As observation time increases, the total noise contributions of read noise and photon noise attenuate, but speckle noise does not, establishing a high noise floor that cannot be reduced without removing the speckles themselves. **I propose to develop a computational method of speckle subtraction for data taken with the Gemini Planet Imager (GPI), which will improve the precision of existing data and will enable future higher-contrast observations of exoplanets.** In addition to improving the sensitivity of legacy data, the proposed work will provide timely support for the funded GPI upgrade beginning in 2020 and returning to science operations with commissioning of GPI 2.0 in 2023.

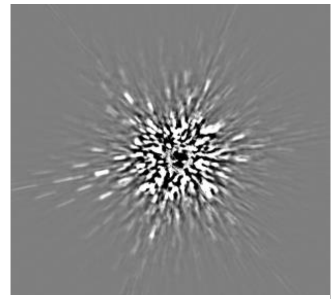

Fig. 1: Raw image of the planetary system HR8799. Four Jupiter-size planets are obscured by quasi-static speckles. Image: Dr. C. Marois

<u>Study Design:</u> Speckle noise is created as starlight passes through non-uniform atmosphere and optics, producing a stellar PSF that varies with time. Atmospheric speckles can only be corrected by improved adaptive optics hardware. This leaves "quasi-static" speckles caused by non-common path aberrations within the instrument optics. Quasi-static speckles change slowly over timescales of minutes to hours [3], resulting in an effect that varies both chromatically and temporally.

This project aims to model, and subsequently remove, these quasi-static speckles using the non-parametric technique of principal component analysis (PCA). PCA identifies "principal components" as linear combinations of input parameters, producing a dimensionally reduced result which identifies the strongest predictors of the features of that data. These results can be used to subtract the quasi-static speckles directly. Previous applications of PCA to high-contrast imaging (e.g. [4, 5]) have focused on subtracting the entire stellar PSF, both atmospheric and quasi-static speckles, which is useful for recovering target signal but results in improvement for only the dataset it's applied to. **The technique of applying PCA to isolated quasi-static speckle noise has never been successfully applied to exoplanet high-contrast imaging, but will result in a more flexible, broad correction for this type of noise.** By characterizing quasi-static speckle behavior and evolution over given epochs and wavelengths, corresponding corrections can be applied not only to the training data, but any data of matching instrument, epoch, and wavelength. This method may also reveal stable speckle behavior which is present at all times and wavelengths, and can be universally subtracted. Once applied, the precision of legacy data is expected to improve by one order of magnitude, and this speckle subtraction will allow future GPI observations to achieve greater contrast by approximately two orders of magnitude [6], making important steps towards accessing Earth-like planets. The phases of this project are outlined below.

<u>Phase I</u>: First, I will build a training dataset of GPI science images containing isolated speckle noise, which can be achieved by subtracting a noiseless model of the stellar PSF from all training data. This will leave only unexplained noise behind, the primary component of which is quasi-static speckle noise.

<u>Phase II</u>: Grouping the training dataset over discrete time increments and wavelength intervals, I will apply PCA to the training data. The results of this analysis can be used to subtract an estimate of the stable components of quasi-static speckle noise from the data. Phases I and II will take place during years 1 and 2 of graduate school, which is well-timed to inform the concurrent GPI upgrade.

<u>Phase III</u>: Then, I will quantify the effectiveness of this correction procedure by measuring the improvement of the intrinsic noise present in each subtracted image, as well as by performing injection-recovery tests with simulated planet signals.

Phase IV: Finally, once these results have been verified, I will develop and release an open-source codebase for quasi-static speckle subtraction, intended for use by scientists working with GPI data. Phases III and IV will take place during years 3 and 4 of graduate school, which will align with the commissioning of GPI2.0 allow for my results to be folded into its data reduction pipeline.

One anticipated challenge associated with Phases I and II is that speckle noise is difficult to isolate in legacy GPI data, either because accurate reference PSFs cannot be generated, or because the data contains systematics which may confuse the subsequent analysis. In this case, since GPI will be present at Notre Dame for upgrades, I will be able to collect data directly from the instrument using the telescope simulator operated by the Chilcote group. By allowing more control over observing conditions and precise knowledge of the input PSF, data taken using the telescope simulator will enable a cleaner first-step analysis, allowing more robust treatment of the legacy data when it is later re-introduced. Another anticipated problem is that GPI2.0 goes on-sky before Phase IV concludes. However, modifications to the processing pipeline can still be made after science operations commence since post-processing can be retroactively applied. Additionally, even if completion of Phase IV lags, the robustness and impact of this technique will be well understood from Phase III, and observations can be planned in anticipation of the correction tools of Phase IV being completed in the future.

Intellectual Merit: The importance of increased contrast for high-contrast imaging campaigns is crucial even beyond exoplanets, with implications for the direct imaging of all astrophysical objects at small angular separations from a comparatively bright source — including circumstellar disks, stellar winds, or jets emitted from neutron stars, pulsars, or black holes. **This project is a high-impact, far-reaching, and low-cost avenue to increasing the science yield of existing direct imaging instruments**, increasing the sensitivity of extant and future data without the need for the expensive and prolonged development of new instrumentation. Additionally, while the proposed solution will be built specifically for GPI, it can be adapted to interface with other ground-based high-contrast imaging instruments, including SPHERE on VLT and CHARIS on the Subaru Telescope. A software-based speckle subtraction method also has strong implications for the development of space-based direct imaging missions, such as the Nancy Grace Roman Space Telescope (formerly WFIRST), as speckle noise is similarly dominant in space-based direct imaging [7]. **The open-source release of my work will facilitate broad advancement and collaboration across astrophysics subdisciplines and different instrument teams.**

Years of previous research experience, including publishing papers, presenting at conferences, giving talks, and directing analysis, have prepared me to effectively execute the proposed work. I have years of experience with data analysis and visualization with Python, and as part of my work with CERN and GPI have worked with large datasets and distributed computing. I currently work on GPI with Professor Jeffrey Chilcote at the University of Notre Dame, so I am familiar with the instrument and am prepared to hit the ground running. I will also benefit from the technical expertise and support of the international GPI collaboration as I develop this project. Given the large volume of legacy data which will be analyzed during this project, as well as the computationally demanding nature of PCA, I will require access to high-performance computing facilities such as the Notre Dame Center for Research Computing.

Broader impact: The NSF GRFP will support me to pursue high-impact research alongside community engagement. Alongside this speckle suppression project, I will establish a peer mentorship program at my graduate institution, as well as develop curricula and workshops to engage public elementary students in space science, both of which I detail in my personal statement. I will integrate these engagement efforts with the GPI Outreach team to create science communication materials conveying the excitement of squinting through stellar glare to find new worlds orbiting underneath.

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