Astrophysics Enabled by Extreme Contrast Ratio Technologies

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MOTIVATION

The most compelling questions in modern astrophysics now require the use of advanced data collection techniques that overcome the problems associated with extreme contrast ratios (ECRs). Internal/external coronagraphy, nulling interferometry, integral field spectral deconvolution and spectral differential imaging are all high-contrast ratio techniques each with their own advantages and disadvantages. For example, the need for high wave-front quality, precise pointing control, additional support structures, and multiple apertures, all lead to significant costs and complications. Software based PSF modeling like LOCI provides some incremental gains in faint point source detection when used with other methods, and the KLIP/ALICE approaches are limited to NICMOS/CORON observations. Consequently, new, cheap, and easy to implement techniques that can suppress the PSF and enable extreme contrast ratio imaging, would be of great benefit.

KEY SCIENCE QUESTION(S)

The direct imaging of an Earth-like planet around another star is probably the most obvious aim for our cosmic origins understanding. However, to image an exoearth one must be able to spatially separate the planet and star, so high resolution is required. In addition, the signal from the planet will be very low so high sensitivity is required. Finally, the magnitude differences between an exoplanet and host star are extreme so ECR imaging is needed. In the case of the Sun-Earth system the difference is 23 magnitudes requiring a $10^{9.2}$ contrast ratio. Consequently, effective PSF suppression is also required for small inner working angles (IWAs). These effects make this type of observation prohibitively challenging from the ground, and it is clear that space-based instruments are required.

In addition to exoearths, there are binary or multiple star systems. Here the compelling question is with ***the binarity fraction of massive stars and the incidence of sub-stellar companions.*** There appears to be three times as many massive stars ($M > 2M_\odot$) in binary systems than that of stars with $0.1 < M_\odot < 2$. Could faint stars fall below detection limits set by bright stars and contrast ratios, or could this result come from the way multiple star systems form? Simple surveys of stellar systems could make significant progress on this question, and potentially (as a by-product) *find planetary systems, debris disks, and any faint nebulosity from pre- or post-main sequence evolution.*

There is also the question of ***the universality of the initial mass function.*** Ground-based studies struggle to detect a population of faint cooler low mass stars peaking in the IR, especially in extinguished systems that are close to the galactic plane. If there is a significant population of low mass companions to massive stars, could this change the form of the low mass end of the IMF?

Continuing, there is ***the characterization of circumstellar materials like remnant protostellar and secondary debris and exozodical light.*** An ECR survey would provide a new opportunity to closely study the end phases of pre-main sequence evolution, the proto-planetary environment, and the long-lived diffuse exozodi (that may be fed by collisions and cometary outgasing). Constraints on models of exoearth resonant signatures could also be made.

Finally, there is ***the relationship between nuclear activity and galaxy evolution***. Previous active galactic nuclei host studies have dealt with bright central sources (accreting supermassive black holes) by making less extreme contrast ratio observations. While studies have had some success in determining the properties of host galaxies, they use sophisticated techniques that rely on time intensive observations with HST.

TECHNICAL CAPABILITIES

- Spectral coverage: UV/visual to near-IR.
- Spectral resolving power, Angular resolution, Field of view: Can be budget limit driven.
- Primary operational mode: Survey.
- Sensitivity: Can be budget limit driven.
- Other important capabilities: Direct extreme contrast ratio imaging.

RELEVANCE OF THE FOUR MISSION CONCEPTS

There is a clear application for ECR technology onboard the Habitable-Exoplanet Imaging Mission and UV/Optical/IR Surveyor, and likely the Far Infrared Surveyor. All of these facilities could address the science questions posed.

NEW TECHNOLOGIES

In angular differential imaging the image plane is rotated with respects to the field due to an Alt-Az mounting. Objects within the field therefore rotate while the features of the PSF remain fixed. Therefore, such data can be combined to create a PSF model that is then removed from the original data. These data are then derotated and combined to produce a field in which the detrimental effects of a bright point source have been suppressed. In roll subtraction a difference image is created from data with the spacecraft at two roll angles. In this case the bright source subtracts out leaving other objects in the field. ***Roll differential imaging*** (RDI) combines both of these approaches. The spacecraft is orientated to at least three roll angles and the field imaged at each. A median-combined PSF model is then created, normalized, and divided out of the individual data frames. These frames are then combined in order to show other features in the field. Features that are stationary in the field would be highlighted in the median combined data, and features that have moved appear in the summed image. Consequently, future missions should include the ability to roll the spacecraft ~+/-15 degrees within a single visit, keeping the telescope fine-locked on a single pixel in the main imager that is placed at the principle optical axis in the field-of-view. This is a technique that is currently being quantified using HST archival data. We estimate this technique to be at TRL-6/7.

Separating the signals of relatively bright and faint targets is a significant challenge for standard MOS arrays because, in addition to the PSF suppression required, the directly achievable CRs are primarily determined by the full well depth of the pixels and limited to CR $< 10^5$. However, the latest generation charge-injection device (CID) are capable of directly producing ECRs $> 10^9$; the SpectraCAM XDR (SXDR). The detector consists of an array of X-Y addressable photosensitive MOS capacitor elements that are individually read out when they approach their full-wells. As a consequence they have an intrinsic 32-bit dynamic range. CIDs are currently at TRL-3, but should achieve TRL-7/8 during 2016 due to an ISS 2U NREP mission manifested for Space X-9 (CRS-9).

LARGE MISSION NEEDED?

A mission concept design study that includes RDI and CIDs is being proposed, but preliminary studies indicate a properly equipped 8-m monolithic Cassegrain design could meet the requirements of the key science questions above. This configuration could fit inside the oversized fairings of the future heavy lift launch vehicles. As this design is simple and uses high TRLs, the budget for such a mission could come in close to, or perhaps less than, $1B.