Scientific Design of a High Contrast Integral Field Spectrograph for the Subaru Telescope

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ABSTRACT

Ground-based telescopes equipped with adaptive-optics (AO) systems and specialized science cameras are now capable of directly detecting extrasolar planets. We present the expected scientific capabilities of CHARIS, the Coronagraphic High Angular Resolution Imaging Spectrograph, which is being built for the Subaru 8.2 m telescope of the National Astronomical Observatory of Japan. CHARIS will be implemented behind the new extreme adaptive optics system at Subaru, SCExAO, and the existing 188-actuator system AO188. CHARIS will offer three observing modes over near-infrared wavelengths from 0.9 to 2.4 μm (the y-, J-, H-, and K-bands), including a low-spectral-resolution mode covering this entire wavelength range and a high-resolution mode within a single band. With these capabilities, CHARIS will offer exceptional sensitivity for discovering giant exoplanets, and will enable detailed characterization of their atmospheres. CHARIS, the only planned high-contrast integral field spectrograph on an 8m-class telescope in the Northern Hemisphere, will complement the similar instruments such as Project 1640 at Palomar, and GPI and SPHERE in Chile.

Keywords: Exoplanets, Integral Field Spectrograph, High Contrast Imaging, Adaptive Optics, Coronagraphy

1. INTRODUCTION

The past seventeen years have seen the discovery of over 700 planets around stars other than the Sun, commonly called "exoplanets" (see `www.exoplanets.org`). Most of these exoplanets have been discovered by the radial velocity variations they induce in their host stars, or through periodic stellar dimming due to planetary transits. Both methods are most sensitive to planets on short-period orbits. The magnitude of a radial velocity signal decreases with increasing orbital period, while large-separation planets must be exquisitely aligned to transit our line-of-sight from Earth. In addition, both of these indirect methods generally require follow-up for one or more orbital periods, which could be centuries for a long-period exoplanet.

With the development of high-contrast, high angular resolution imaging, large telescopes can now directly image giant planets at large distances from their host stars.[1–4] The addition of spectroscopy to direct imaging will enable the characterization of giant exoplanet atmospheres and the development of techniques to find Earth-like planets that may support life.[5] This contribution describes the science case for CHARIS, a new Integral Field Spectrograph (IFS) designed for taking spectra of exoplanets, to be built for the Subaru 8.2 m telescope. CHARIS will simultaneously obtain spatial and spectral information over the field-of-view (FOV) by dispersing the entire image on the detector. CHARIS will be the first high-contrast IFS on an 8m-class telescope in the

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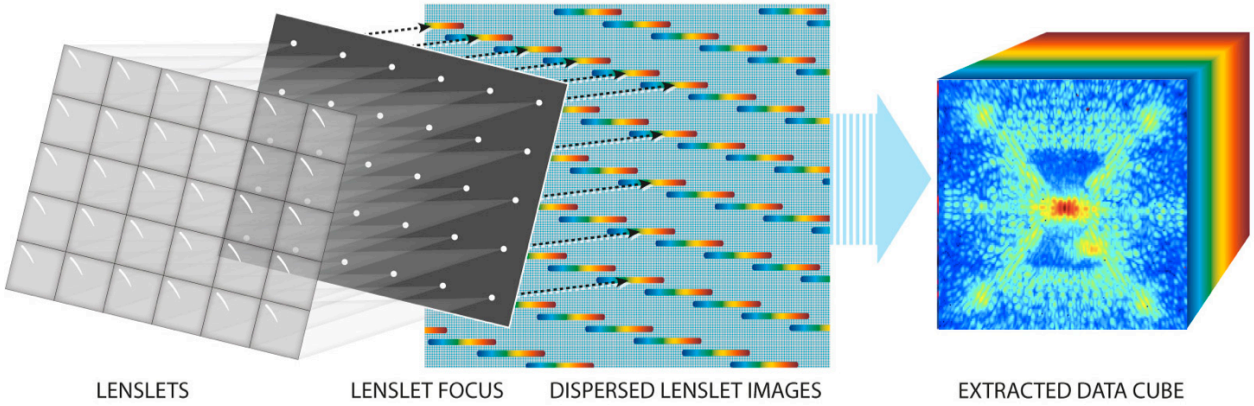

Figure 1. How a lenslet-based IFS works. A lenslet array at a focal plane within the instrument focuses the incident light into a grid of well-separated points. A pinhole mask at the lenslet's focal plane blocks diffracted and scattered light. Each lenslet's focused light is then dispersed onto a Teledyne H2RG detector in such a way that they do not overlap. Finally, a data cube is extracted: a spectrum at each spatial location in the FOV.

Table 1. CHARIS Specifications

Spaxel Scale		0.″0126 (2λ/D at 0.9 μm)	
Spectral Range			0.9 – 2.4 μm
Observing Mode	low-R	medium-R	high-R
Spectral Resolution	14	33	65
Bandwidth	1.5 μm	0.7 μm	0.4 μm
Detector	2048 × 2048 HgCdTe Hawaii 2RG		
Field of View			1.″75 × 1.″75

Northern Hemisphere, and will achieve an inner-working angle $\sim 2\lambda/D$ and contrasts of up to 10^{-7}. CHARIS will provide both a low-resolution (R = 14) mode in which it will simultaneously collect photons from λ=0.9-2.4 μm, and a high resolution (R = 65) mode over a single near-infrared bandpass: y-, J-, H- or K-band.

The technical design of the instrument is described in the accompanying paper.[6]

2. CHARIS SPECIFICATIONS

CHARIS is a lenslet-based IFS designed for high-contrast imaging and spectroscopy. The instrument produces a spectrum for each spatial element (spaxel) and thereby a data cube of the observed field, with two spatial and one wavelength dimensions (see Figure 1). The basic design follows that of the first astronomical IFS TIGER[7] but incorporates innovations such as specialized lenslets to reduce crosstalk between the spectra of neighboring spaxels. Table 1 lists the key specifications of the CHARIS IFS.

CHARIS is part of a third-generation suite of high-contrast instrumentation at the Subaru telescope, and will be the first high-contrast IFS on an 8-m class telescope in the Northern Hemisphere. Its primary competitor in the Northern Hemisphere will be Project 1640[8] on the Palomar 200″. It will complement the similar instruments currently being built for the Southern 8-m class telescopes: the Gemini Planet Imager (GPI[9,10]) and the Spectro-Polarimetric High-Contrast Exoplanet Research instrument (SPHERE) on the Very Large Telescope VLT-Yepun.[11–13]

3. HIGH CONTRAST INSTRUMENTATION AT SUBARU

The Subaru telescope's infrared Nasmyth platform currently houses a 188-actuator AO system (AO188) and a high-contrast near-infrared science camera (HiCIAO[14]). SCExAO, the Subaru Coronagraphic Extreme AO project,[15,16] received first light on 5 February 2011 and is currently under commissioning. When fully finished,

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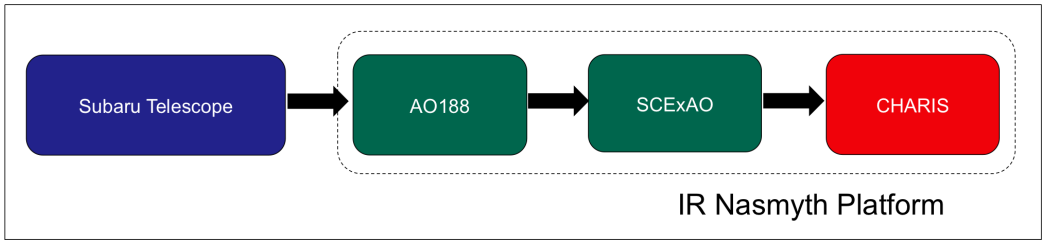

Figure 2. Layout of the third-generation high-contrast instrumentation suite at Subaru's infrared Nasmyth platform.

SCExAO will provide high-order wavefront correction with sophisticated coronography using techniques such as phase-induced amplitude apodization (PIAA[17]) and shaped pupil coronagraphs (SP[18]). Further contrast improvements will be made with focal plane wavefront sensing techniques such as speckle nulling,[19] dramatically improving contrast at small inner working angles. SCExAO will initially feed its beam into HiCIAO for imaging, immediately improving HiCIAO's performance at small separations ($< 0.2''$). The flow chart in Figure 2 shows the layout of the third-generation high-contrast instrumentation suite at Subaru's infrared Nasmyth platform, with CHARIS replacing HiCIAO as the science camera.

4. THE SEEDS PROJECT

SEEDS, the Strategic Exploration of Exoplanets and Disks with Subaru, led by P.I. Motohide Tamura, is the first of Subaru's strategic programs. The project uses HiCIAO for high-contrast imaging in the H-band (1.6 μm). SEEDS will ultimately survey ∼500 nearby stars to detect and characterize planets and disks around them.[20] SEEDS has already discovered substellar companions of several Jupiter masses around young nearby stars, one example of which is shown in Figure 4. HiCIAO operates in several modes:

1. Polarimetric differential imaging (PDI) to detect and map the scattered light from planet-forming disks around young stellar objects (YSOs)[21–23] and from debris disks;
2. Angular differential imaging (ADI) to search for point sources, i.e., self-luminous giant planets; and
3. Spectral differential imaging (SDI), in which HiCIAO simultaneously images in four narrow sub-bands that straddle the H-band CH_4 feature. SDI is also used to provide higher contrast in the search for point sources.

Most of the SEEDS work to date has been carried out in the PDI and ADI modes; see for example the detection of a cold substellar companion to the nearby G8 star GJ 758.[24,25] The SDI mode has been deployed occasionally for follow-up observations (e.g., R. Kandori et al., in preparation). HiCIAO SDI splits the bands in intensity with a Wollaston prism, and then passes the beams through either two or four narrow sub-bands that straddle the H-band CH_4 feature. In this mode, each SDI narrow band has only ∼10% of the bandpass of the broadband H filter. HiCIAO's SDI mode thus gains spectral information at the cost of 90% of the incident H-band photons.

Figure 4 shows the ADI and SDI images of GJ 758 and its companion, GJ 758 B. This is a precursor for the images that CHARIS will produce. By dispersing all of the incident light in its low-spectral-resolution mode, CHARIS will avoid HiCIAO's tradeoff between spectral information and sensitivity to faint sources. The spectral data provided by CHARIS will allow both better suppression of speckle noise and detailed characterizations of exoplanet atmospheres, including those of exoplanets discovered by SEEDS.

5. CHARIS FIELD-OF-VIEW AND SPECTRAL RESOLUTION

CHARIS will accept its beam from the extreme AO system, SCExAO, which will produce a high Strehl ratio (and hence, high contrast) over a wavelength-dependent radius of about $1''$. This, the detector size, and the sampling at the shortest wavelength (the y-band at 0.9 μm), set our FOV to be $\sim 1\farcs75 \times 1\farcs75$ (Table 1). At 10 pc, $1''$ corresponds to a distance from the star of 10 A.U., so CHARIS with SCExAO will probe planetary system scales similar to those of the giant planets in the Solar system.

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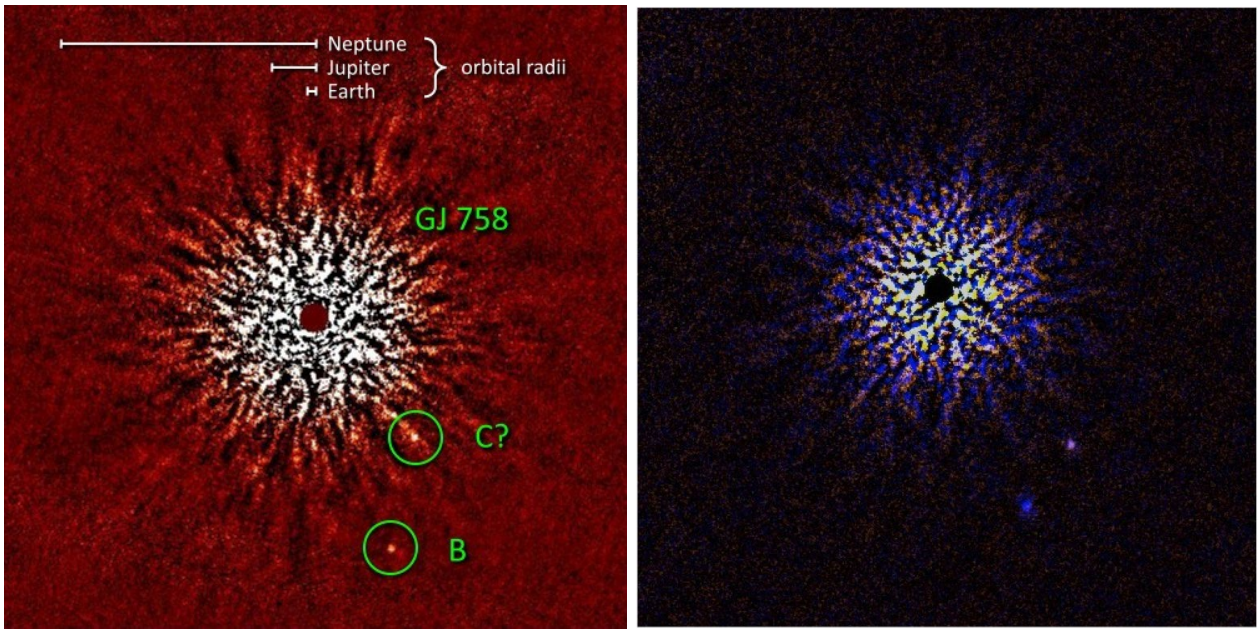

Figure 3. Discovery of the cold substellar object GJ 758 B. *Left image*: Subaru AO188+HiCIAO ADI H-band observation.[24] *Right image*: Combined SEEDS AO188+HiCIAO SDI image of GJ 758 in CH_4-on (red) and CH_4-off (blue), showing the spectral information obtained in adjacent narrow-band filters (R. Kandori et al., in preparation). GJ 758 B shows dramatically different fluxes in and out of the methane band, represented here by red and blue, respectively. The background star (indicated by "C?" in the left image and confirmed as a background source by a common proper motion test) has similar fluxes in CH_4-on and CH_4-off, showing no evidence of a methane feature. SDI and IFS data products are capable of detecting and spectrally characterizing detections in a single observation.

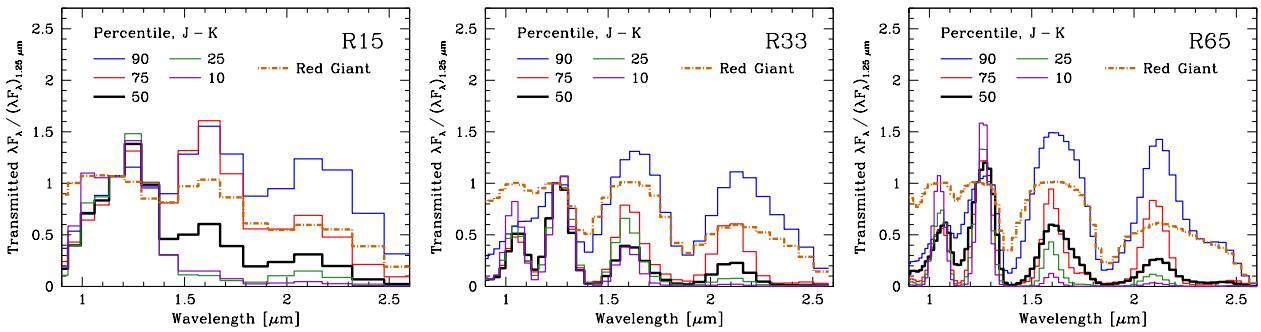

Figure 4. Model exoplanet spectra with a range of $J-K$ spectral indices, convolved with the atmospheric transmission at Mauna Kea and scaled to the count rate at the CHARIS detector. We overplot a relatively featureless red giant spectrum for comparison.

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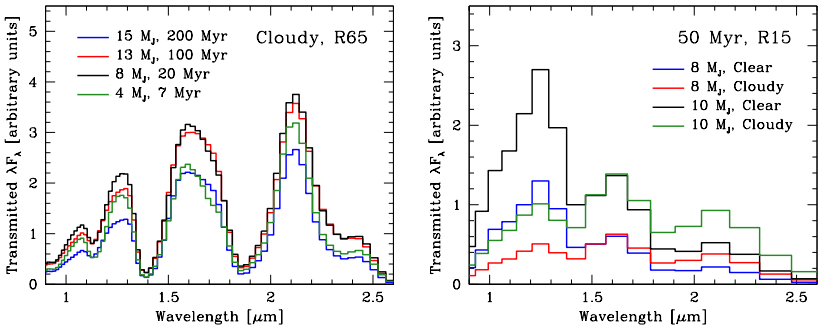

Figure 5. *Left panel*: Model exoplanet spectra[26] as observed with the CHARIS high spectral resolution mode, showing the strong degeneracy between age and mass. *Right panel*: If a planet has a well-determined age, even low-resolution spectra provide strong constraints on the mass and insights into atmospheric properties. The planet and its host star are assumed to be coeval; observations of the host star provide the age constraints.

The selection of spectral passbands and resolution has been informed both by recent spectroscopic observations of free-floating substellar objects (the brown dwarfs), which serve at least in part as proxies for the properties of giant exoplanets,[27] and by detailed models of giant-planet atmospheres.[26] Figures 4 and 5 illustrate these models for exoplanets of a range of masses, ages, and assumed initial conditions. According to these models, the spectra in the K- and H-bands provide the best diagnostics of the planetary initial conditions. Two mechanisms have been proposed to form giant, large-separation exoplanets: the core-accretion model,[28] and the gravitational instability model.[29] These two models predict different thermodynamic conditions in the newly formed exoplanets; spectra covering the full wavelength range from 0.9 to 2.4 μm, together with well-determined system ages, will thus be able to discriminate between them. We therefore decided to include the K band (2.2 μm) in CHARIS despite the potential for thermally induced noise.

The current conceptual design for CHARIS covers the near-infrared from the y- to the K-band. Our baseline design provides a spectral resolution of R = 33 with a bandpass of $\Delta\lambda = 0.7$ μm ($J + H$ band or $H + K$ band). The calculations and simulations shown in Figures 4 and 5 suggest two additional modes:

1. R = 15 with a $\Delta\lambda = 1.4$ μm bandpass, allowing CHARIS to measure the full wavelength range from the y- to the K-band simultaneously (left panel of Figure 5); and
2. R = 65 with a $\Delta\lambda = 0.4$ μm bandpass, which allows higher-resolution observations in each of the bands and the measurement of important atmospheric spectral diagnostics such as H_2O, CH_4, and CO (right panel of Figure 5).

CHARIS will change its spectral resolving power by switching dispersive elements and changing its bandpass filter. All three configurations will contain 140×140 spaxels and 16 spectral measurements. In all three modes, the plate scale at the lenslet array will be 12.6 milli-arcseconds (mas, $0\farcs001$), such that the shortest wavelength of $\lambda = 0.9$ μm is Nyquist sampled. Details are given in the companion paper.[6]

6. CHARIS DATA PRODUCTS

A CHARIS observation will produce a data cube of the FOV with one spectral (λ) and two spatial (x, y) dimensions. Calibration spots produced on the detector by a coarse diffraction grid in SCExAO will provide 3 mas astrometry with respect to the target star and spectrophotometric calibration with respect to the target star's spectral energy distribution.

Figure 6 shows a simulated data cube calculated for a one-hour observation in low-spectral-resolution mode of a young solar-type star at a distance of 10 pc. The FOV includes three faint objects: a companion giant planet, and two background stars. As Figure 6 shows, a single low-resolution observation can distinguish between exoplanet and stellar spectra, similar but more efficiently than in the SDI case (see Figure 4), which is only sensitive to the CH_4 feature. The exoplanet has much less flux at short wavelengths than the much hotter stars,

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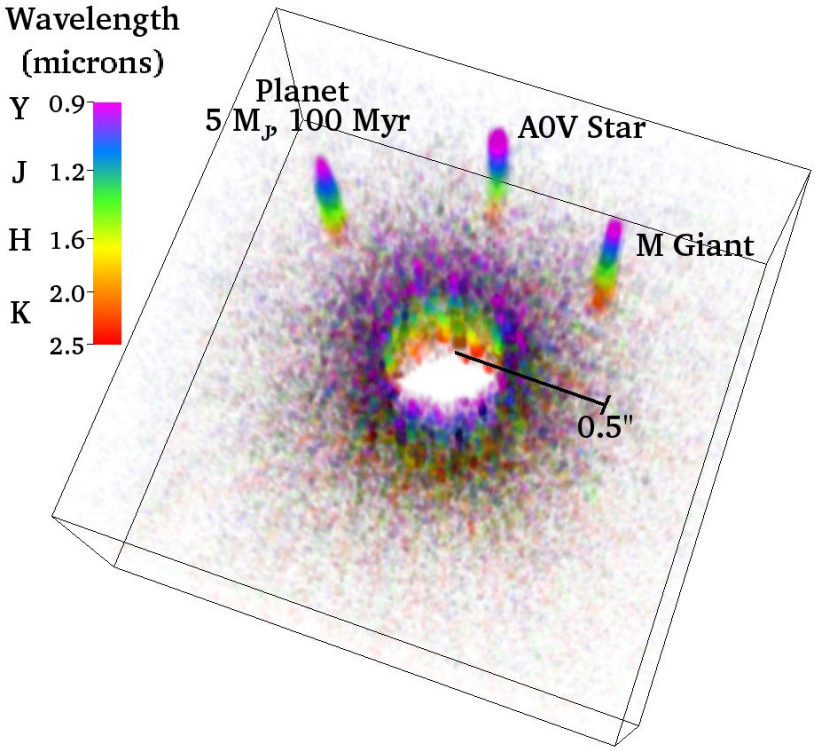

Figure 6. A simulated low-spectral-resolution CHARIS datacube showing three point sources in the observed field of a solar-type star aged 10^8 years and at a distance of 10 pc. The point sources are all 10^6 times fainter than the central star and are at a spatial separation of $\sim 0.5''$. The 5 M_J, 100 Myr planet clearly displays spectral features, including a much lower flux at short wavelengths, which distinguish it from the background stars. The two background objects are an A0V star and an M giant, both of which have relatively featureless spectra in the near-infrared.

and also has stronger spectral features. Any background star would be hot enough to make its near-infrared spectrum nearly featureless. An observation like that shown in Figure 6 would be followed up to test for common proper motion and to characterize the exoplanet's atmosphere using CHARIS' high-spectral-resolution observing mode.

7. SENSITIVITY

We have estimated the performance of SCExAO+CHARIS relative to that of AO188+HiCIAO using a one-hour on-sky integration for a fifth magnitude star as our fiducial observation (Figure 7). SCExAO will improve the H-band Strehl ratio from $\sim$30% to $\sim$90%. However, SCExAO, combined with CHARIS, will suffer a factor of $\sim$3 loss in throughput relative to AO188+HiCIAO. On the other hand, CHARIS will be able to take longer exposures due to the higher Strehl ratio, increasing the observing efficiency and reducing the effects of read noise. In its low spectral resolution mode, CHARIS will collect photons over a much wider bandpass than can HiCIAO. These factors combine to increase the limiting sensitivity of SCExAO+CHARIS relative to that of AO188+HiCIAO by a factor of $\sim$10, assuming perfect subtraction of the host star and no coronagraph.

The SCExAO performance shown in Figure 7 only measures the hardware improvements from the AO system and from CHARIS' spectral coverage. SCExAO will also implement advanced coronagraphy and speckle suppression techniques,[30–34] which only become possible with the high Strehl ratios it will attain. In practice, SCExAO+CHARIS could even out-perform the limits shown.

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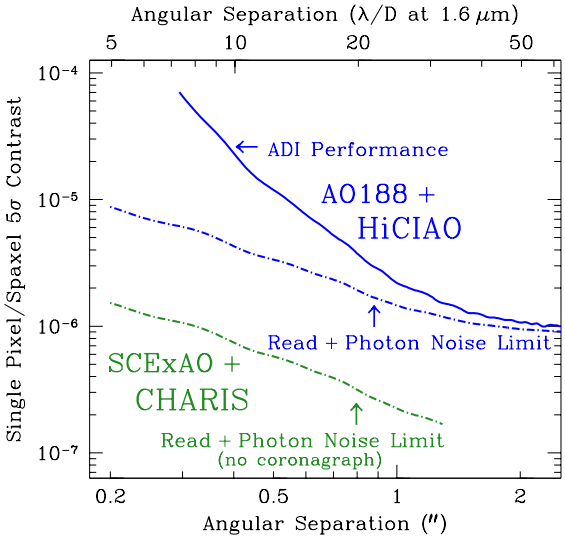

Figure 7. Contrast curve for the existing AO188/HiCIAO system (blue) and expected for the combination of SCExAO+CHARIS (green). We show both HiCIAO's limiting performance assuming perfect subtraction of the host star and its performance in actual observations. CHARIS' limiting performance will be a factor of ∼10 better with no coronagraph, and with the advanced coronagraphic techniques SCExAO will implement, CHARIS could even out-perform the limits shown. SCExAO + CHARIS will push inward toward 1 λ/D with the PIAA coronagraph.

8. CHARIS SCIENCE

CHARIS is designed to detect and characterize giant planets in systems around nearby stars. In combination with SCExAO, it will dramatically improve contrast relative to AO188+HiCIAO from separations of $\sim 1''$ down to an inner working angle which is essentially Subaru's diffraction limit of 2λ/D ($\sim 0\farcs02$, depending on wavelength). If the target star has a well-determined age, even the low-spectral-resolution mode will provide a well-determined planetary mass. As Figures 4 and 5 illustrate, the atmospheres of giant planets are expected to show a great deal of spectral diversity due to the effects of age, metalicity, clouds, and formation conditions. The spectral characteristics are highly degenerate in age and mass, and the properties of young planets, which are far easier to detect because they are brighter, depend in addition on whether the planet was formed via instabilities in the circumstellar disk ("warm" start) or via core accretion ("cold" start).[26]

CHARIS, along with the similar instruments SPHERE and GPI in the Southern Hemisphere and Project 1640 in the Northern Hemisphere, will enable surveys and observations which will clarify our understanding of the formation and evolution of giant planets. Many uncertainties remain regarding exoplanets, from the formation mechanism itself, to the frequency of exoplanet systems with distant, giant planets, to the dynamical evolution of such systems. Data from IFSs like CHARIS will constrain exoplanet masses and atmospheric conditions and will uncover the frequency of exoplanet systems, as well as their dependence on the host star's age and metalicity. This will constrain protoplanetary disk models which seek to understand the formation of planets and sub-stellar objects in the outer disk and the coevolution of the planets and the disk.

9. SUMMARY

CHARIS will be the first IFS for exoplanet studies on an 8m class telescope in the Northern Hemisphere. It will achieve a small inner working angle ($2\lambda/D$), and high contrasts of up to 10^{-7}, representing a factor of $\gtrsim$10 improvement over the current, second-generation high-contrast instruments on the Subaru telescope. CHARIS will provide R = 33 spectral resolution over a $1\farcs75 \times 1\farcs75$ FOV. It will also provide both a low-spectral-resolution mode (R = 14), able to collect imagery from $0.9 - 2.4$ μm, and a high-spectral-resolution mode (R = 65) over a single near-infrared bandpass.

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CHARIS will offer exceptional sensitivity to detect new exoplanets, and high contrast and spectral resolution to provide detailed characterizations of their atmospheres. It represents a major advancement in exoplanet science and will help address uncertainties in the frequency, properties, and formation mechanism of giant exoplanets. The instrument should achieve first light at the Subaru telescope by the end of 2015.

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