Detection and Characterization of Extra-solar Planets

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Scientific category:	EXTRASOLAR PLANETS
Instruments:	NIR/CAM, NIR/SPEC, MIR/CAM, MIR/SPEC
Days of observation:	425

Abstract

Abstract: We suggest a suite of NGST studies aimed at the detection and characterization of planets over a range of mass, age, stellar spectral type, and physical separation from their central stars. The results of these studies will constitute fundamental steps toward an understanding of the origin of planets and life in the universe, and, in particular, will lay the groundwork for future NASA missions such as the Terrestrial Planet Finder.

Observing Summary:

Target	RA	Dec	K_{AB}	Configuration/mode	Days
350 NEARBY STARS	d<25pc	Resolved		MIR/CAM R3-R10	15
200 YOUNG STARS	d=150pc	Resolved		MIR/CAM R3-R10	10
100 NEARBY STARS	d<25pc	Resolved		NIR/CAM R3-R10	150
50 EXTRA-SOLAR PLANETS OR BROWN DWARFS	d<25pc	Resolved	0.1-1μJy	NIR/SPEC R3000-R10000	50
50 EXTRA-SOLAR PLANETS OR BROWN DWARFS	d<25pc	Resolved	0.1-1μJy	MIR/SPEC R3000-R10000	50
50 EXTRA-SOLAR PLANETS OR BROWN DWARFS	d$\sim$100 pc	Resolved	0.1-1μJy	NIR/SPEC R3000-R10000	50
50 EXTRA-SOLAR PLANETS OR BROWN DWARFS	d$\sim$100 pc	Resolved	0.1-1μJy	MIR/SPEC R3000-R10000	50
50 EXTRA-SOLAR PLANETS	d<25pc	Unresolved	700μJy	MIR/SPEC R30000	50
				Grand total days	425

Scientific Objectives

Precision radial velocity searches for extra-solar planets have revealed an unexpected diversity in planetary masses, orbital radii, and eccentricities. In the light of these discoveries, our solar system appears to represent only one example of a planetary system, and possibly one that is not very typical. This implies that in our attempt to understand the origin of planets and life everywhere in the universe, focusing solely on the properties and origin of solar system bodies may prove too restrictive in scope. Instead, it appears that there is a clear need for a comprehensive census of planetary companions (e.g., over a range of orbital separations, planetary masses, stellar spectral types, etc.), and a characterization of their physical properties in order to explore the full range of conditions under which planets might currently exist, have originally formed, and be capable of supporting life.

To this end, the spectroscopic study of planetary atmospheres is a powerful tool that allows us to measure the physical properties of planets such as temperature, gravity, and chemical composition, and thereby provides important clues to planetary age and the formation process. For example, the formation of planets through gravitational collapse favors a planet of solar composition, while formation via an accumulation scenario, as commonly adopted to explain the origin of solar system planets, favors a planet enriched in heavy elements. By probing the physical properties and chemistry of planetary atmospheres, spectroscopy can also begin to address issues such as habitability.

We propose 3 programs for the detection and characterization of extra-solar planets: (1) Detection via imaging in thermal planetary emission and reflected stellar light. (2) Spectroscopy of bright, spatially resolved brown dwarf and giant planet companions within a few 100 pc that will characterize the physical properties of extra-solar planets and develop our understanding of planetary atmospheres over a wide range of physical conditions. (3) Detection and characterization of spatially unresolved planetary companions using high resolution spectroscopy. The spectroscopic detection of the planet in these systems will allow the measurement of planetary mass and orbital inclination, as well as provide a preliminary investigation of the properties of the planetary atmosphere.

Detection via Imaging in Thermal and Reflected Light:

1 Background, Goals:

As is well-known, planetary atmospheres have contributions from reflected stellar light, which dominates at short wavelengths ($\simeq 2\mu$m), and planetary thermal radiation, which dominates at long wavelengths ($>2\mu$m), both of which offer opportunities to probe the physical nature of the planet. Through direct imaging studies of substellar companions in either reflected or thermal emission, NGST has the potential to measure some fundamental physical properties of extra-solar planets. These results will be highly complementary to the results of astrometric studies (e.g., with Keck and SIM). For example, planetary radii obtained from imaging photometry, when combined with planetary masses inferred from astrometry, will yield the planetary bulk density, a fundamental physical parameter.

Hot young planets, or more massive brown dwarfs, are luminous enough to study in their own thermal emission at wavelengths near 5μm, where the low methane and water atmospheric opacities conspire to produce a local flux maximum in the planetary spectrum. With brightnesses 10^4–10^6 fainter than their central stars, these objects will be relatively easy to detect with a coronagraph in nearby star forming regions (at orbital separations $r > 50$ AU) or around stars within 10 pc ($r > 5$ AU). More challenging but also more significant is the possibility of detecting Jupiter-mass planets in reflected light within 10 pc, a task which demands instrumental contrast levels of 10^9 within a few arcseconds on the central star. These contrast levels can be achieved by NGST between wavelengths of 1–2μm using a coronagraph to control diffraction, plus a high acuator density deformable mirror to correct the stellar wavefront and thus control scattered light.

2 Observing Strategy:

We will use NGST enhanced by a coronagraphic near-IR camera to study substellar companions in the solar neighborhood, and luminous young protoplanets associated with nearby young stars. All 350 Gliese catalog stars within 10 pc will be surveyed for brown dwarf companions in 5μm thermal emission. We will be able to detect 1 Gyr old 20 M_J objects if they are present within 5 AU of each object. In nearby star-forming regions, 200 young (< 5 Myr) stars will be surveyed for companions as small as a Jupiter mass to within 50 AU also at 5μm. From both samples, detected objects will be spectrally characterized using broad and medium band filters, especially those that measure the strengths of molecular bands such as CH_4 and H_2O. These programs will together require about 25 days of telescope operations. The results will be used to make a preliminary assessment of the properties of the planet as well as the test theories of low-temperature brown dwarf and extra-solar planetary atmospheres. Detections from this program will provide additional targets for the spectroscopic program discussed in the next section.

We also propose a survey for Jovian planets in reflected light at orbital separations $r \simeq$ 5 AU for 100 of the brightest and/or nearest Gleise catalog stars. Data from ongoing astrometric surveys will be used to suggest high-priority targets. This program will require the advanced coronagraph instrument. Each star will be observed twice during a year, providing a temporal baseline to establish proper motion associations between and candidate companions and their host star. Performance simulations indicate that the median integration time per object per visit will be 0.5 days, for a total of 100 days in the initial survey. In the nearest/brightest systems, Saturn and Uranus sized planets will be detectable; searches for them can by initiated by taking deeper images. Addional observation epochs for detected objects will track the orbital motion, and follow-up observations in broad-band filters will provide color indices. The exact amount of follow-up time required depends on the (unknown) frequency at which planets are detected, thus we tentatively allocate 50 additional days for these studies.

3 Why NGST?

The two key elements needed for the direct detection of extra-solar planets are large telescope apertures and a stable point spread function of the highest possible Strehl ratio. High-order wavefront correction is required to suppress scattered light from mirror surface irregularities and/or atmosphere-induced phase errors. In space, mirror wavefront errors can be measured, corrections applied, and integrations performed for hours or days without recalibration; in a ground-based AO system, atmospheric instability limits the temporal validity of any wavefront corrections to just a few milliseconds. Only a large-aperture space telescope, such as NGST equipped with a wavefront-correcting coronagraphic camera, can routinely achieve the required contrasts of 10^9 within radii of a few arcseconds from bright stars.

Spectroscopy of Spatially Resolved Planets:

1 Background, Goals:

We will characterize the low-temperature atmospheres of extra-solar planets using moderate resolution spectroscopy. The robust determination of the physical properties of the planets will rely on broad spectral coverage, which is needed for the recovery of fundamental quantities such as temperature and composition structure and surface gravity, as has been the case in the study of Jupiter. For example, spectral coverage at NIR and MIR wavelengths offers the opportunity to study multiple chemical species and thereby facilitates the simultaneous determination of the vertical temperature and composition structure. Specific wavelength regions can be used to focus on specific regions of the atmosphere. Using the case of Jupiter as a guide, cloud properties can be probed by albedo effects in the optical and near-IR, the 5μm region probes the deep troposphere below the cloud deck, and the 6–15μm region probes the upper troposphere and lower stratosphere.

The spectroscopic results will play a fundamental role in our understanding of planetary atmospheres over a range of physical conditions. For example, ongoing theoretical efforts (e.g., Burrows et al. 1997, Marley et al. 1998) which build on our knowledge of solar system planets are currently constructing models of planetary interiors and atmospheres over the wide range of masses, ages, orbital separations, and metallicities that are expected to characterize the extra-solar planet population. However, as is well-known, planetary atmospheres are complex systems in which relatively poorly understood physical processes such as stellar irradiation effects, cloud condensation and rain out, and planetary meteorology (e.g., vertical circulation) strongly affect the physical nature and spectral appearance of the atmosphere. For example, in the case of Jupiter, solar irradiation produces a temperature inversion in the upper planetary atmosphere and drives a rich photochemistry that alters the chemical composition and spectral appearance of the atmosphere. In the more general case of other planetary systems, stellar irradiation effects will obviously vary strongly with orbital separation. Given the complexity of planetary atmospheres, actual observations of extra-solar planetary atmospheres will be critical in solidifying our understanding of these systems, especially in physical situations in which the solar system planets cannot provide an accurate guide.

2 Observing Strategy:

We will study a range of orbital separations, stellar spectral types, and companion masses. In addition to objects with planetary masses, our survey will include brown dwarfs in order to characterize the continuum of low-temperature atmospheres, and thereby improve our understanding of the physics that govern them. As stepping stones to the eventual understanding of planetary atmospheres, we imagine our analysis of the data as proceeding from isolated brown dwarfs (examples of low temperature atmospheres), to brown dwarf companions (low temperature, externally irradiated atmospheres), and finally to planetary companions. In the time estimate for this program, the spectroscopic time to study isolated brown dwarfs is not included since it is already a part of the DRM proposals to study the stellar IMF. We include the discussion of these objects only for conceptual completeness.

Nearby objects: For nearby (e.g., < 25 pc) objects (e.g., discovered from the ground or with SIRTF or NGST), we will obtain spectra over a broad spectral range (1–20μm) and at moderate resolution (R=3,000–10,000) in order to characterize their atmospheres at a level comparable to that obtained for planets in our solar system (e.g., ISO Fabry-Perot R=20,000; Cassini CIRS R=3000 7-1000μm). This will allow us to compare in detail the vertical temperature and chemical composition structure of solar system and extrasolar planets. There are approximately 4000 stars within 25 pc. If 5% have brown dwarf or giant planet companions, we will have a sample of 100 objects from which to choose appropriate targets. A 1 Gyr old $1 M_J$ giant planet at 10 pc will be $\sim 1\mu$Jy at 5–10μm (Burrows et al. 1997). Typical exposure times are 1×10^5s for SNR=15 at R=10000. A 5 Gyr old $1 M_J$ giant planet at 10 pc will be $\sim 0.1\mu$Jy at 5μm and essentially undetectable at shorter wavelengths (Burrows et al. 1997). Typical exposure times are 4×10^5 s for SNR=10 at R=3000.

Distant, younger objects: By expanding our census to include more distant systems, we will be able to explore younger, more luminous brown dwarfs and extra-solar giant planets in young clusters (e.g., TW Hya 60 pc, 20 Myr; Pleiades 120 pc, 100 Myr) and star-forming regions (e.g., Taurus, 150 pc, 1 Myr) that will be discovered from the ground or in SIRTF surveys. We will use R=1000–10,000 spectra to determine surface gravities, composition, and effective temperatures in order to place the objects on HR diagrams for comparison with theories of giant planet formation and early evolution. Since the mass function of low mass objects is unknown, it is difficult to predict the number of sources that will be available for study. We conservatively estimate several 100 sources from which to choose appropriate targets. A 100 Myr old 1 M_J giant planet at 100 pc will be $\sim 0.1\mu$Jy at 4–10μm. Typical exposure times are 4×10^5s for SNR=10 at R=3000 at 5μm. It would be feasible to study more massive objects at higher spectral resolution. A 100 Myr old 5 M_J giant planet at 100 pc will be $\sim 2\mu$Jy at 4–10μm. Typical exposure times are 1×10^4s for SNR=10 at R=10000 at 5μm.

3 Why NGST?

High spatial resolution is needed for the spectroscopy of close companions. The MIR is where the contrast between planet and star is best; NGST will excel and be unique here. The MIR also provides unique diagnostics of planetary atmospheres over a range of depths, from the deep troposphere to the stratosphere.

Spectroscopic Detection of Spatially Unresolved Companions

1 Background, Goals:

We will use the high sensitivity of NGST in the MIR to spectroscopically detect spatially unresolved planetary companions to nearby stars, such as those discovered by precision radial velocity techniques. The measurement of the radial velocity of the planet will allow a direct measurement of the planetary mass and orbital inclination. In addition, the detection of planetary spectrum will allow a preliminary characterization of its atmosphere.

2 Observing Strategy:

The MIR is the wavelength region of choice, since the contrast between the planet and star are maximized. To further maximize the contrast between the planet and star, we will target warm planetary companions with effective temperatures ∼1000K, as would be expected for either massive young planets or planets with small orbital separations such as 51 Peg b (e.g., Guillot et al. 1996). Although the contrast at wavelengths beyond 5μm is still presents a challenge, detections are possible by simultaneously observing many lines in the planetary spectrum (∼100). By obtaining spectra at multiple phases in the orbit and phasing the spectra at the known orbital period, we will increase the detectability of the planet as well as confirm its orbital motion.

The resolution requirement is set by the need to resolve the motion of the planet in its orbit. To resolve planetary motions of ±50 km/s, a resolution of R≥10,000 is needed. Higher spectral resolution maximizes the detection of lines in the planetary atmosphere. If the planet has the same angular momentum history as Jupiter (not at all certain!) so that it rotates at a similar rate ∼10 km/s, an upper limit to the required spectral resolution of R=30,000 is implied. To estimate the target sample size, we assume that ongoing and future precision radial velocity surveys which will have sample sizes of thousands of stars will detect close planetary companions in ∼3% of the systems, comparable to the detection rate in ongoing surveys, resulting in a sample of ∼50 close companions.

The simulation above (Figure 1) demonstrates the ability of NGST to undertake this program. In the simulation, a K0V star at a distance of 10 pc with a bright Jupiter-mass companion is observed at 5μm at R=10,000. The flux ratio between the planet and star is 6700 at this wavelength. The system is observed for 1×10^4s at each of 5 orbital phases and it is assumed that the spectral coverage is broad enough that 200 lines (100% deep; intrinsically

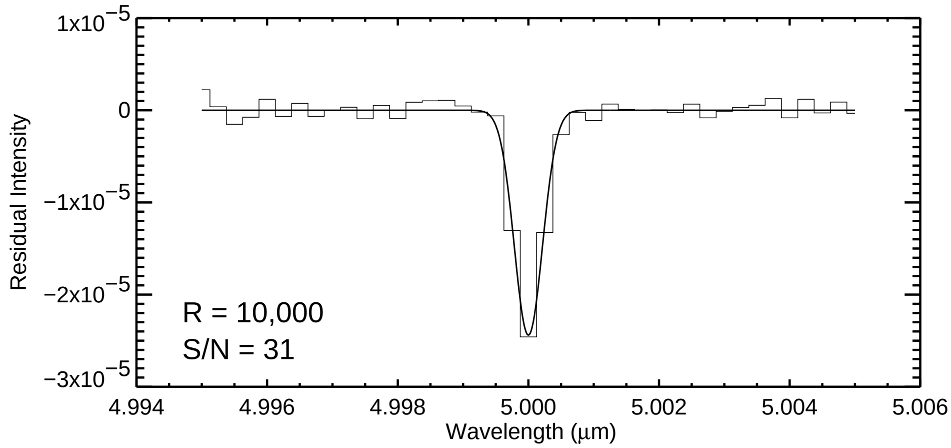

Figure 1: Simulation demonstrating the ability of NGST to detect spatially unresolved planets around nearby stars, e.g., 51 Peg b. The simulation shows the co-added signal from 200 absorption lines in the planetary spectrum. The planetary contribution to the composite spectrum is detected at high SNR despite the bright continuum of the central star. The simulation assumes spectral coverage sufficient to detect several hundred lines in the planetary spectrum, and that the observation is at thermal IR wavelengths where the planet vs. star contrast is most favorable. Such observations would provide a direct measurement of planetary masses, orbital inclination, and atmospheric composition. See text for details.

5 km/s wide) from the planetary spectrum are observed. Although the planetary spectrum is a tiny fraction of the continuum, it is detected at SNR=31. For R=30,000, the same experiment yields SNR=52, i.e., each line is detected at SNR=4.

3 Why NGST?

The MIR is where the contrast between planet and star is best; NGST will excel and be unique here. There are numerous planetary diagnostics in the MIR. NGST is uniquely suited to the study of this spectral region at high SNR.

Special Requirements

Program 1: High spatial resolution imaging with a well-characterized PSF. Coronagraphic capability is highly advantageous, and necessary for the detection of close companions.

Program 2: Moderate (R=1000) to high (R>10,000) spectral resolution capability in the near and thermal IR (1-20μm) is required to characterize the atmospheres of spatially resolved companions. Since the spectrum of extra-solar giant planets is fairly flat from 5-10μm (e.g., Burrows et al. 1997), longer wavelengths offer improved contrast against the central star. Broad wavelength coverage is needed for the robust determination of the depth dependence of the atmospheric temperature and composition. Techniques to minimize scattered light from the primary (e.g., coronagraphy) also a plus.

Program 3: For the direct detection of spatially unresolved, known extra-solar planets within $\sim$ 1AU of their central stars, high spectral resolution (R>10,000) is required to resolve the motion of the planetary companion in its orbit ($\sim$50 km/s) in order to confirm detection of the planetary atmosphere. Since the planet to star contrast ratio is best in the mid-IR, spectroscopic capability in this wavelength region is critical for this program.