Next Generation Space Telescope

Ad-Hoc Science Working Group
Design Reference Mission Proposal

Detection and Characterization of Jovian Planets and Brown Dwarf Companions in the Solar Neighborhood

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Scientific category: EXTRASOLAR PLANETS
Instruments: NIR–MIR/CAM+CORONAGRAPH
Days of observation: 97

Abstract

We describe a key NGST Origins science program, the study of giant planet and brown dwarf companions to single stars within 20 parsecs of the Sun. These substellar objects can be directly detected from their superthermal emission in the $\lambda = 4.6 - 5.1$ μm molecular opacity window through the use of a graded-mask Lyot coronagraph and the nominal NGST wavefront. Combining the emergent fluxes from recent giant planet/brown dwarf atmosphere models, stellar data from the Gliese catalog, and a detailed model of coronagraph performance for the case of a seven segment primary mirror, we find that NGST will be capable of imaging planetary companions of Jupiter's mass, age, and orbital semi-major axis around all single stars within 8 pc of the Sun in integration times of three hours or less. We propose (1) A survey of the nearest 180 single stars for Jupiter-like companions complete to 8 pc, (2) A more extensive survey of the nearest 500 single stars for more luminous (younger and/or more massive) companions that will be nearly complete to a 5 μm flux level 4 magnitudes brighter than Jupiter, and (3) Detailed spectrophotometric study of selected objects discovered in these two surveys. These observations can be expected to provide the first determination of the giant planet/brown dwarf luminosity function, the first spectral characterization of these objects across a broad range of effective temperatures, and the first direct images of planets orbiting another star. The results will be of fundamental importance to our understanding of planetary systems and their frequency in the galaxy.

Observing Summary:

Target	RA	Dec	K_{AB}	Configuration/mode	Days
180 NEARBY SINGLE STARS, D<10PC				OTHER	45
500 NEARBY SINGLE STARS, D<20PC				OTHER	21
70 BROWN DWARFS/PLANETS COMPANIONS				OTHER	31
				Grand total days	97

Scientific Objectives

1 Background: Brown Dwarfs and Extra-Solar Giant Planets

The discovery of the cool brown dwarf GL229B (Nakajima et al. 1995) has led to a major resurgence of interest in the faint end of the stellar luminosity function. Brown dwarfs (BDs) are gaseous objects intermediate in mass between Jovian planets and stars; with masses $\lesssim$0.08 $M_\odot$, they never obtained the core pressures and temperatures required for hydrogen fusion. In addition, the exciting discoveries of planetary companions from radial velocity surveys of solar-type stars (Mayor & Queloz 1995, Marcy & Butler 1998, Cochran et al. 1997) has proved for the first time that other planetary systems exist, and that they can be very different from our own. The large eccentricities and small separations found for many extrasolar giant planets (EGPs) has spurred significant new theoretical research on the formation and orbital stability of planetary systems, and the possible similarities and differences in the formation processes of EGPs and BDs. The detection and characterization of these substellar objects represent a new astrophysical frontier that should produce insights into several key issues such as binary star formation, accretion processes in protoplanetary disks, and the nature of dark matter.

It is generally believed that BDs (like low-mass stars) form through the collapse of dense molecular cloud cores, and that planets form in circumstellar disks through coagulation of planetesimals; however we currently do not know the range of companion masses that can be produced by these two formation mechanisms, or if those two ranges overlap. An upper limit to the mass of planets may be determined by the limited supply of material available in proto-planetary disks. Unfortunately, our understanding of these issues is extremely poor because the number of detected BDs/EGPs remains quite small. A decade of extensive observational effort has been rewarded with today's capability to detect and study *isolated* brown dwarfs in their own instrinsic thermal emission. However, the detected objects are either relatively young (age $<$ 1 Gyr) or massive ($\sim$ few $\times$ 10 M_J). For fainter (older or less massive) objects, the detection statistics are dismal: only one cold (T_{eff} <1000K) "methane" brown dwarf has been found so far. No BD/EGP companions have been directly detected in the 0.3-30 AU range of separations corresponding to planets in our solar system.

Significant advances will require the ability to obtain a reasonably complete census of BDs/EGPs, both in isolation and in orbit around stars (e.g. covering a range of masses, primary star spectral type, and orbital separations). As a followup to such a survey, spectra of a range of different BDs/EGPs are highly desirable to constrain their physical properties, including temperature and luminosity as a function of age, their gravity, and the presence of molecules in their atmospheres. Detection and characterization of EGPs is an important first step that NGST can provide in the study of other planetary systems – a major theme of NASA's Origins program.

2 The role of NGST

Full-sky ground-based infrared surveys such as DENIS and 2MASS are steadily building up the detection statistics for isolated brown dwarfs. Large telescopes and interferometers with adaptive optics should soon make initial direct detections of BD companions of nearby stars. However, such observations will be limited to the bright end (high mass/low age) of the BD luminosity function, and to wide binary separations for the detected companions. Indirect search techniques such as radial velocity or astrometric measurements of the primary star provide important complementary information (the companion's minimum mass, and its orbital period), but also suffer selection effects toward higher masses and short orbital periods. The indirect techniques provide no photons from the BDs/EGPs, leaving us to speculate as to the luminosity and spectral character of these new worlds.

A major opportunity for observational progress is offered by the NGST. Its unsurpassed sensitivity at near- and mid- infrared wavelengths, combined with its high spatial resolution and stable PSF, will facilitate pioneering work that includes the detection and characterization of substellar companions of nearby stars. These capabilities are not contemplated for any other observatory that will be available before the end of the next decade. SIRTF will have the sensitivity to detect isolated BDs, but lacks the spatial resolution to distinguish them as companions on solar-system scales. Large ground-based telescopes with adaptive optics will offer the angular resolution needed to resolve BD companions from their parent stars, but their high backgrounds and contrast limitations will restrict their contributions to the most luminous objects at the largest separations. With the proper instrumentation, NGST can bridge this gap by facilitating the direct detection of substellar companions of nearby stars, including objects whose masses and ages are comparable to our own Jupiter and Saturn, and whose orbital positions fall in the range of 5-10 AU. Direct detection has the added advantage that it is no more difficult to detect a complex planetary systems with multiple planets than a single planetary companion. It provides the means to further investigate many planetary systems discovered in groundbased radial veleocity searches, including the recent discovery of three EPGs around υ Andromedae (Butler et al. 1999) and others that will inevitably be discovered in the next several years.

In designing our observing program, we lean heavily on coronagraphic instrument performance models being developed by the NGST/ISIM HCOSS concept study group (Trauger et al. 1998). We have computed detailed estimates of the NGST optical performance that include with a measure of conservatism the optical characteristics and operational precedures presently anticipated for NGST. A seven-hexagon deployed primary mirror is assumed, following the system architecture study of TRW. Provision is made for wavefront correction on the primary mirror, with up to 394 actuators working on each hexagonal segment according to the Arizona mirror design concept (Angel and Burge 1999). The optical alignment procedures of D. Redding (private communication) are implemented as follows. First, the seven individual mirror segments are assigned surface figure errors with power spectral densities (PSDs) ten times worse than expectations based on recent experience with large astronomical mirrors. Next, the seven randomly misaligned mirror segments are brought into alignment by wavefront retrieval of a star image. Finally, the mirror actuators are used to further refine the optical wavefront through phase retrieval of a star image, but with actuator positional errors of 10 nm added randomly to simulate the performance of the Angel and Burge (1999) actuator concept. This alignment procedure terminates once the diffraction limit is achieved at 2 μm wavelength. We emphasize that *no further wavefront corrections* are assumed for this proposal beyond this basic NGST optical requirement.

3 Proposed programs

We propose an observing program to identify and characterize jovian planet and brown dwarf companions around nearby stars using an NGST coronagraph. By detecting planetary photons directly, NGST will provide the first opportunity to spectrally characterize exoplanet atmospheres. In conjunction with mass determinations for the companions from astrometric surveys, NGST observations will allow the theoretical cooling curves for substellar objects to be compared with actual luminosity and temperature measurements. Finally, by taking the first direct images of planets orbiting other stars, NGST will help bring NASA's Origins program to the attention of the general public.

The effects of scattering and diffraction in the instrument are combined with backgrounds from solar system zodiacal emission and emission from the telescope primary to estimate the background level against which a planet must be detected. Shot noise on this background and detector noise are combined together to estimate integration times for planet detection at $S/N = 10$. This is a somewhat conservative detection criterion, since planets will always appear as point-like images whereas residual speckles take on a spectrally dispersed and streaked appearance in broad-band images. Additional image processing with spatial filtering should provide better sensitivity, but is not assumed in our feasibility criterion. Exposure times are calculated for actual Gliese catalog objects, using their apparent mangitudes and distances.

Early in the HCOSS study, it became clear that 5 μm is an especially attractive wavelength for the study of Jovian planets and brown dwarfs. At this wavelength the atmospheres are significantly cleared of molecular opacity, allowing thermal emission from warmer, deeper levels of the objects to escape directly to space. It has long been known that Jupiter's disk shows broad "hot spots" in 5 μm images (Ortiz et al 1998). The spectrum of GL229B also shows a prominent flux enhancement at 5 μm (Oppenheimer et al. 1998). Theoretical spectra from model brown dwarf atmospheres consistently show the same bright emission near 5 μm, and indicate that these objects can be *many orders of magnitude* brighter than an equivalent blackbody radiator at the planet's effective temperature (Burrows et al. 1997; Allard et al. 1997). For example, the 5 μm contrast between a Jupiter-like companion and an M star primary (such as Lalande 21185) is just 6×10^6. The superthermal emission of EGPs and BDs at 5 μm offers a distinct opportunity for planet detection that NGST should exploit.

(1) Search for Planets

We will search for giant planet companions in a sample of nearby single stars (d<10 pc). This search will be aimed at detecting EGPs at least as bright as Jupiter (i.e. $mass = 0.001$ $M_\odot$, $age = 4.5$ Gyr, absolute M magnitude 23) at separations of 5 AU. Using a 10% bandwidth M filter, the survey will be able to detect Jupiters around **all** single stars within 8 pc, and around a significant fraction of others stars at greater distances. Detection of more luminous (more massive, or younger) or more widely separated companions will be correspondingly easier, and can be accomplished for progressively more distant systems from the Sun. To observe 180 targets (90 of them within 8 pc), this program will require a total of 45 days of integration time. With integration times of $\leq$3 hr/object, the search will include detections of planets with Saturn's brightness and orbital radius in 10% of the systems within 8 pc. We will also carry out "target-of-opportunity" observations towards stars which show evidence for well-separated EGP companions, such as the those found orbiting υ Andromedae by Butler et al. (1999).

(2) SNAPSHOT Search for Extra-Solar Giant Planets/ Brown Dwarfs

We will carry out a search for brown dwarf companions in a sample of nearby single stars (d<20 pc) in the M band. This search will be aimed at detecting BDs/EGPs brighter than an absolute M magnitude of 19. For reference, either a young 1 M_J object at ~ 1 Gyr or a more massive 5 M_J object at ~ 5 Gyr would have an absolute M magnitude of 19. Using relatively short integration times ($\leq$0.5 hr/object) will allow us to carry out this survey in a SNAPSHOT observing mode reminiscent of HST, for a total of 21 days of integration time. We expect to obtain a nearly complete census of BDs/EGPs ($\gtrsim$77%) in our sample (about 500 objects assuming a $\sim$50% attrition due to objects with stellar binary companions, and excluding those included in program 1). Since the brightnesses of BDs/EGPs depend on both their masses and their ages, each observed magnitude defines a curve in the mass-age plane.

(3) Characterization of Planets and Brown Dwarfs

For the brightest objects uncovered in the two surveys above, we propose spectroscopic or spectrophotometric observations from $\lambda = 1 - 20\mu$m. For the 50 brightest brown dwarfs, we will take $R = 100$ slit spectra using the coronagraph's spectral mode. For the 20 brightest EGP companions, which will be significantly fainter, we will employ filter photometry only. The power of such observations for developing a detailed understanding of BDs has been demonstrated by recent observational and theoretical results on GL229B, where modeling of its strong methane (CH_4) and water (H_2O) absorption bands between $1 - 4\mu$m have provided constraints on the temperature, composition, mass, and age of the brown dwarf though comparison with a grid of atmosphere models coupled to an evolution/cooling code. NGST will thus enable us to probe the initial mass function for star formation well below the main sequence boundary. The presence of clouds in these atmospheres can modify the spectrum in the 5 μm window (and in other near-IR windows), producing a more greybody spectrum depending on the particle size. The abundant water molecule is expected to be the primary cloud-forming constituent for $T_{eff} < 400$K; ammonia also becomes important for $T_{eff} < 150$K. At $T_{eff} > 400$K, EGP atmospheres should be relatively clear of major cloud decks, until ∼1000K when silicates become relevant. Whether or not clouds will play a major role below 400K is uncertain, as Jupiter shows strong 5 μm emission through its very patchy water and ammonia clouds. The proposed $R = 100$ spectroscopic observations would provide the critical foundation for future theoretical studies which can help resolve cloud formation issues.

We estimate that we will require integration times of about 10 hours per object to obtain spectra with sufficient signal-to-noise to detect the major absorption bands due to water, methane, ammonia and phosphine expected in the $(1 - 20)$ μm region. For the 20 brightest planetary companions, we will carry out observations with additional filters at 1.6, 4.5, 5.1, and 12.8 μm, with integration times of 3 hr/filter. This program will thus require a total of 31 days of integration time.

Acknowledgements
We thank Mark Marley (NMSU) for computing spectra in support of this study.

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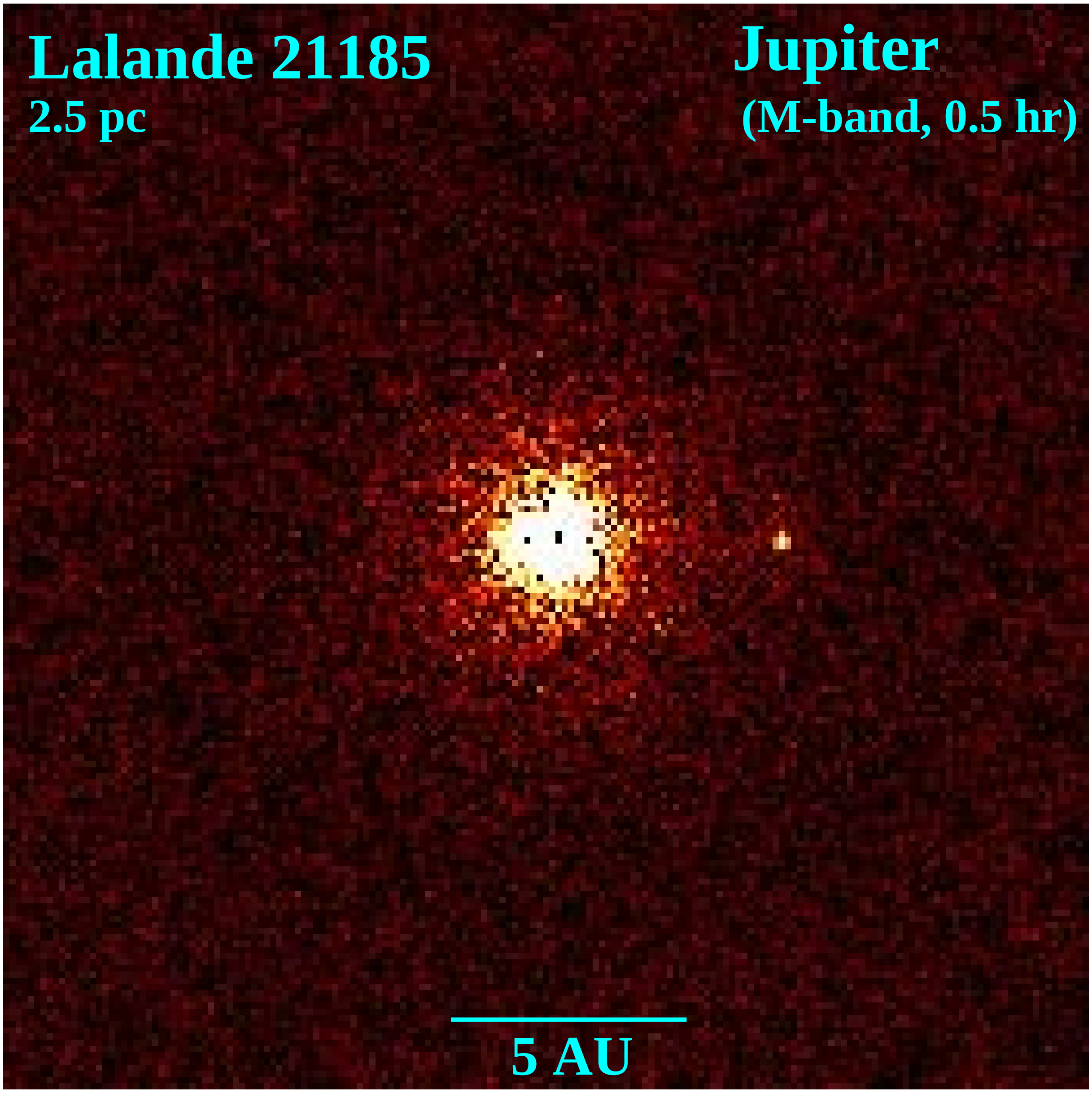

Figure 1: Simulated NGST detection of a planet of Jupiter's brightness at 5 μm orbiting Lalande 21185, a nearby (2.5 pc) main-sequence M2 dwarf. The planet is assumed to have an orbital radius of 5 AU. A coronagraph is used to attenuate the glare of the primary star. The simulation uses the most up-to-date descriptions of NGST background and detector noise contributions, a 10% filter bandwidth, and 50% overall thruput.

NGST Uniqueness/Relationship to Other Facilities

The substellar companions targeted in this proposal are fainter than their primary star by factors of more than 10^6, and are separated by at most a few arcseconds. To image with such high contrasts and small separations requires a large, diffraction limited telescope with a very stable PSF. While 8 meter class ground-based telescopes with adaptive optics will achieve the necessary angular resolution, their Strehl and hence achievable contrast at small separations is seriously limited by uncorrected high-order phase errors that lie beyond the capabilities of practical groundbased (kilohertz rate) adaptive optical systems. Of still greater importance is the large (factors of 100 or more) reduction in sky and telescope background which NGST provides at the advantageous observing wavelength of 5 μm, where the contrast between the planet and star is most favorable. While ground-based observations should progress in the coming years with detections of additional luminous brown dwarfs companions at relatively large angular separations from their parent stars, only NGST offers the prospect for directly detecting objects of Jupiter's luminosity and orbital separation in the solar neighborhood.

Observing Strategy

The two discovery surveys will be conducted in a 10% bandwidth filter centered at 4.8μm, similar to the standard M band. The M-band is the window of choice for the survey observations because it provides the largest signal-to-noise ratio for detection. At shorter wavelengths the planet flux is significantly lower, whereas at longer wavelengths the thermal background is signficantly higher. We have verified this conclusion by computing the coronagraphic performance at different wavelengths. Each target will be observed at two epochs separated by 6 months. Multiple spacecraft roll angles will be used to help discriminate detected objects from residual speckles in the NGST diffraction pattern. True companions will be identified by observing their common proper motion with the central star over the 6 month baseline. In estimating our sensitivity, we have made the conservative assumption that the substellar companion is located 45 degrees of orbital longitude from maximum elongation. This makes the observation more difficult, but ensures that planets will be detected in more than 70% of the systems where they are present. Filters specific to the features in brown dwarf/jovian planet atmospheres will be needed for the spectral characterization of faint substellar companions; these will include a 1.6 μm "methane-free" filter and special filters adjacent to M band to measure the spectral slope of the superthermal emission.

Special Requirements

Observations at multiple roll angles and at least two epochs are required for the two discovery surveys. A fixed slit orientation is likely for the coronagraph's low resolution spectrograph mode. This will result in narrow observing windows during which a substellar companion could be placed on the slit while the primary star is simultaneously behind the coronagraphic mask.