In Search of New Worlds: NASA's Astronomical Search for Origins[1]

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Abstract— A curiosity for who we are…, where did we come from…, who else is out there…, has been a motivation for exploration from ancestral gatherings around the tribal fire to sophisticated musings at the "electronic hearth" of our computers. NASA's Astronomical Search for Origins (ASO) science theme has brought together a broad array of scientific investigations and technological means to address these most challenging questions. ASO's goals are to understand how galaxies formed in the early universe, to understand how stars and planetary systems form and evolve, and to determine whether habitable or life-bearing planets exist around other stars in our solar neighborhood. This last goal, to find and to characterize planets and planetary systems around other stars, perhaps to image that "pale blue dot" that will be the "new world" of humanity's next era of exploration, this is the purpose of NASA's Navigator Program: *In Search of New Worlds*. This paper describes the missions, the scientific endeavors, and the network of technology investments that are the Navigator Program, and which are at the heart of the Astronomical Search for Origins.

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1. INTRODUCTION

In some primal way, the curiosity for what lies over the hill, what lurks outside the comforting light from our own fire, has driven humanity to step out, to explore and to discover since our earliest history. In modern times, NASA has taken up the challenge of exploring beyond the "hills" of distance between earth and our neighboring planets to understand how they came to be, how they are now, and what might be there. This exploration is conducted in the Solar System Exploration scientific theme. An even more daunting challenge, going beyond the light of our own solar source to search for new worlds, how they came to be, and what signatures of activity might be seen, this is the province of NASA's Astronomical Search for Origins (ASO).

In 1584 the Dominican monk Giordano Bruno, a free-thinker of his time, wrote a treatise called *On the Infinite Universe and Worlds* in which he said:

> *"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth….*

For this visionary thinking, in 1600 in the Campo dei Fiori in Rome, Giordano was burned at the stake. Not to be daunted, ASO today motivates its activities through two questions:

- *Where did we come from?*
- *Are we alone?*

In this quest, ASO has set itself three goals [Ref 1]:

- To understand how galaxies formed in the early universe.
- To understand how stars and planetary systems form and evolve.
- To determine whether habitable or life-bearing planets exist around other stars in the solar neighborhood.

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[1] 0-7803-6599-2/01/$10.00
Paper No. 456.

The first of these goals as well as the star formation part of the second goal are addressed through several ASO missions, including the prolific Hubble Space Telescope, the Space Infrared Telescope Facility (SIRTF) scheduled to launch in 2002, the Stratospheric Observatory for Infrared Astronomy (SOFIA) carried aboard a specially configured Boeing 747 aircraft, and the Next Generation Space Telescope (NGST) which plans to launch large (6m) deployable optics with near- and mid-infrared imaging and spectroscopic instruments in the 2010 timeframe.

The planetary system formation aspect of the second goal, as well as the third goal, are the focus of a set of science, technology and flight mission efforts being conducted in the ASO theme under the Navigator Program: *In Search of New Worlds*, and are the subject of this paper.

2. WHAT WE DON'T KNOW & WHAT WE DO

Just 75 years ago, we didn't know that our galaxy wasn't the entire universe. Fuzzy objects seen in the sky, with the technology available then, were thought to be clouds, or nebulae, floating in our universe. In the 1920's, Edwin Hubble showed that they were in fact "island universes", galaxies, receding from each other at a great rate. This discovery led to an enormous advance in theory and observation in cosmology, fundamental physics and astronomy. Today, the vast array of ground and space-borne observatories continue to explore ever deeper into the universe, transforming what had been a domain of mystery into a field of investigation with a solid base of theory and data.

What we're beginning to know

Just 5 years ago, we didn't KNOW that there are planets "out there". Today, we have confirmed observations of over 70 planetary systems from a survey of around 1000 stars within 30 parsecs of our own, with much of this data obtained from NASA-funded time on the Keck Observatory. So, it appears that about 7% of stars have planets. There are lots of stars, so there are lots of planets.

Looking at Figure 1, one can readily see that most of these planets are really big (0.2 to 15 times the mass of Jupiter, M_J); and most of them are whipping around fairly close to their star (inside 1AU). Is this typical? Is our solar system unusual in lacking these giant pinballs careering around in the habitable zone (HZ: the distance from a star where temperatures are conducive to life)? If there are these close-in giants, what does that mean for smaller rocky planets, like earth, in the habitable zone?

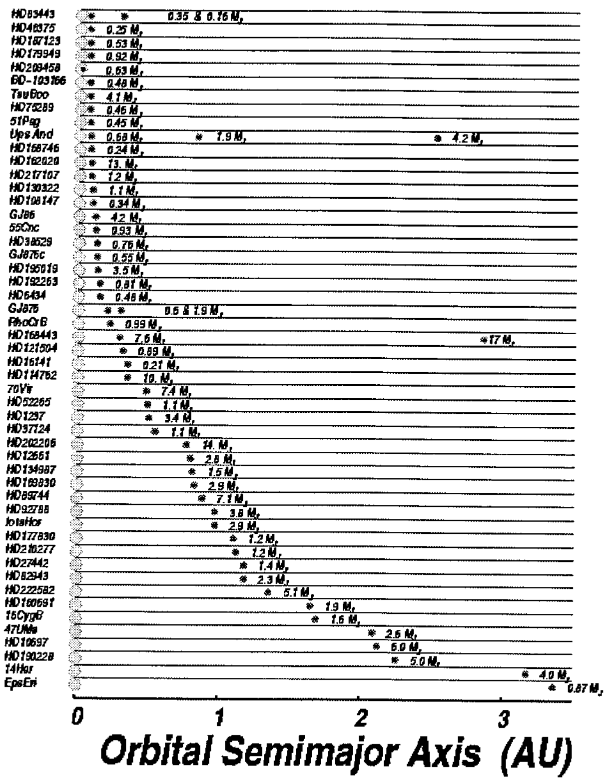


Figure 1 Known Exo-Solar Planets (mass vs. semi-major axis) [Ref 2, w/permission]

How do we know what we know?

As can easily happen in science, the current state of knowledge is biased by a selection effect arising from the nature of the measurements being made and the technology available to make them. Nearly everything we know about planets beyond our own little tribe around our sun has been learned through the technique of radial velocity measurement. Just as a figure skater whirling his partner in an orbit around him on outstretched arms also inscribes his own tiny orbit on the ice, so a planet orbiting a star causes the star to move through a small orbit due to the tug of its gravitational attraction. Depending on the alignment of this orbital arrangement with respect to our telescopes on earth, we can see an apparent motion of the star toward and away from us. The well-known Doppler effect then causes the frequency spectrum of the light from the start to shift higher or lower (redder when the star is moving away, bluer when it's moving toward us) as it moves. From this information taken over a period of time, the mass and orbital distance of the presumptive planet can be inferred. In fact, with enough data and sophisticated modeling techniques, the effects on the star of multiple planets can be discerned.

It is the limitations in our ability to resolve the spectral shift in the stars light that produces the observing bias mentioned above: a massive planet very close to the star makes the star move more than a smaller planet farther away. Also, without knowing the inclination (*i*) of the orbit to our line of sight, we don't really know how much motion is going on. Our estimate of the planetary mass, which is proportional to sin *i*, contains that uncertainty.

What we know we don't know.

So,we know there are a lot of planets. This starts to get at the second Origins goal. Observers are beginning to gather enough data over long enough periods to develop some characterization of multi-planet systems; but, they are limited by the observing bias to those that have big planets close in. So, there's a little advance on the second Origins goal. To get at the third Origins goal, "to determine whether habitable or life-bearing planets exist around nearby stars", there is clearly a lot of work to do.

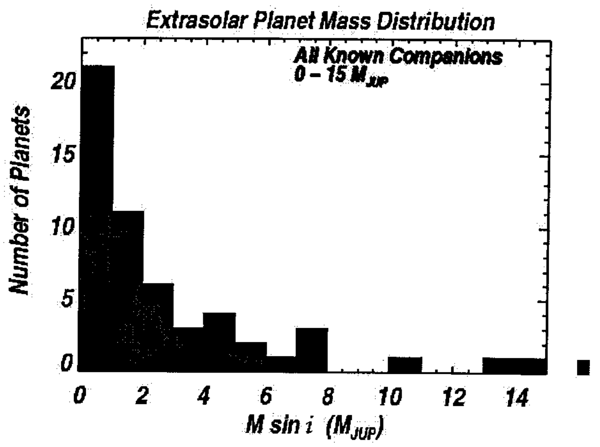
One of the things we want to know is are there planetary systems out there that resemble ours in terms of mass and placement of planets? And, what are the implications of the big, close-in planets to having habitable-sized planets (i.e., the right size to be rocky vs. a gas giant) in the habitable zone (like Goldilocks, not too hot, not too cold, but just right for aqueous chemistry based life). Some modeling studies show that these giant pinballs careering around where we would want our earth to be would throw us out of the system.

We need to know the demographics of planetary systems. There has been a surge of interest in these questions recently, resulting in some serious computer modeling of multi-body planetary systems and theorizing on formation of planetary systems. Some of this work may show that the system needs to be constructed "just so" in order to allow the right size planets in the right places with the right deposition of volatiles to produce a place we would call "home". An excellent treatment of the subject and review of related work in the field has been provided by Lunine [Ref 3].

What we want to be able to find are planets like earth. Fortunately, there are some encouraging trends.

As shown in Figure 2, from Marcy et al., there is a trend toward more planets at lower masses. Whether this trend leads us to lots of, or any, planets like earth remains a challenge for future observational techniques.

To take the next steps, unambiguous knowledge of the masses of the planets must be added to the census database of planetary systems. Techniques that allow resolution of stellar motions at the micro-arcsecond level coupled with spectral resolution to detect possible atmospheric signatures of biogenic origin will allow us to seriously advance on the third Origins goal. We need to know not only the results of these investigations, but first we need to know how to accomplish them. What technologies will allow measurements of such unprecedented precisions?



Marcy, Butler,Fischer,Vogt

Figure 2 Histogram of Planets as function of apparent mass [Ref 2, w/permission].

What we don't know we don't know.

One of the interesting aspects of all of this is how deeply embedded anthropic thinking is in all of us…of course, how could it be otherwise? Just as the universe must be constructed consistent with the fact of our existence, our observation of it must be consistent with that same fact. Certainly scientists are interested in what IS out there; but, how much more interesting if what IS out there were like we would like it to be…that is to say, if it supported life as we conceive it to be. What if the medium for the chemistry of life were non-aqueous? Then where would the habitable zone be? Would rocky planets be necessary? And wouldn't we thrill to the sight of someone looking back?… For the rest of this paper, we will "stay between the lines" laid out in the framework of our theoretical and experimental approach to the search for new worlds.

3.How to Find a Planet

Early efforts in planet finding were based on direct observation. Ancient observers noted the motion of "wanderers" across the otherwise stable configuration of stars, and called them planets. Advances in observational precision through pure determination as well as optical technology supported advances in theory, leading to our fairly good knowledge of our own solar neighborhood today.

However, as good as our techniques are, we are back to "early days" in observing planets around other stars. The radial velocity approach described above has produced seminal results; but, if we are to really develop an ability to not only find, but characterize planetary systems and measure their constituents sufficient to detect the potential for life, great advances in our technology are required.

The "holy grail" for planet hunters is to find **terrestrial planets** (planets about the size of earth, which can be "rocky" in nature and can hold an atmosphere: 0.5 to 2.0 times the mass of earth, M_e) in the **habitable zone** (the distance from the central star where the temperature is right to allow liquid water to exist: about 0.01 to 2 AU for stars less than 3 solar masses, M_0).

Other techniques being employed now or in future investigations include measurement of changes in apparent stellar brightness (planetary transit photometry and gravitational Microlensing), direct angular measurements of stellar motion (astrometry), and direct imaging.

Transit Photometry [Ref. 6]

Transit photometry measures changes in brightness of stars due to planets crossing between the observer and the star. One limitation of this technique arises from the need for a proper alignment of the plane of the planets orbit with respect to observers on or near earth. Assuming a terrestrial sized planet in the habitable zone, the probability of the orbit being properly aligned is about ½%. In order to confirm that a planet has, in fact, been observed, it must be observed three times: the first and second times to establish the presumed orbital period, and then the third time, on the predicted schedule, to confirm the observation. So, only planetary systems lined up just right are observable with this technique; and, only planets with orbital periods within the observing time limits of the investigation can be confirmed. Still, with these limitations it is projected that a suitably designed space-based observatory, such as proposed for the NASA Kepler Discover mission, could find many planets down to the size of earth.

Kepler is designed to survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone. It utilizes a 0.95-meter aperture differential photometer with a 105 deg^2 field of view to continuously monitor photometric variations of 5-40 X 10^{-5} for ~100,000 stars. In addition to the basic science returned, these observations are important to the mainstream NASA planet finding missions discussed later because they help define the requirements for the search, including identifying common stellar characteristics of host stars, defining the volume of space needed for the search (the frequency of terrestrial planets), and by identifying target stars for these high-powered deep searches.

COROT [Ref 7] is a mission approved by the French Space Agency CNES, dedicated to stellar seismology and the study of extrasolar planets. It is planned for launch in 2004. COROT has 1/10 the collecting area of Kepler for photons, 1/20th the field of view of the sky and stares at a given star field for 1/10 the amount of time that the Kepler Mission stares.

Another mission proposed to ESA, Eddington, is somewhat closer to the Kepler Mission in capability. It has almost the same collecting area and hence should achieve similar noise performance for the same star brightness. Eddington is proposed for a 2008 launch.

Microlensing: As predicted by Einstein's General Theory of Relativity, an intervening dim star or other mass can amplify the brightness of a background star. Planets orbiting the intervening star can change the amplification in a detectable manner. This provides another technique for photometric detection of planets, although with even more challenging limitations due to the need to not only have an alignment of the planet's orbital plane, but also to have an intervening lensing mass. This technique is being pursued through both ground and future space-based observations.

Astrometry

Astrometry measures the apparent movement of a star as a planet in orbit around it tugs it. Whereas the Doppler technique measures this motion toward and away from the observer by measuring shift in the wavelength of emitted radiation, astrometry measures that motion from side to side. This technique has the advantage that there is no mass dependence on the orbital alignment. It shares the difficulty of the Doppler technique in that smaller planets and planets farther away produce less wobble and are harder to observe.

The precision of the angular measurements required is awesome. For giant planets around stars out to 10 pc, angular resolution on the order 50 microarcseconds is required. To put this angle in perspective, the width of a typical strand of human hair would subtend 50 microarcseconds if you were viewing it from a distance of 130-190 miles. This is the goal for the proposed NASA FAME (Full-sky Astrometric Explorer) mission. FAME will provide measurements of nearly all stars down to 9th magnitude using a scanning survey instrument evolved from Hipparcos. [Ref 8].

To get down to planets of a few earth masses in the habitable zone, precision on the order of a few microarcseconds is required. The analogy here might be looking from earth, and observing an astronaut on Mars move a laser pointer from one hand to the other. As one might imagine, significant technological challenges lie ahead in this technique.

The promising technique to meet this challenge is interferometry. An interferometer combines the beams from two or more apertures to produce interferometric fringes. Measuring the delay in wavefront arrival at the apertures provides a very precise measure of the angle of the target star with respect to the baseline between the apertures. As indicated in Figure 3 Interferometer

Schematic, this is accomplished by employing a delay line in one of the beams.

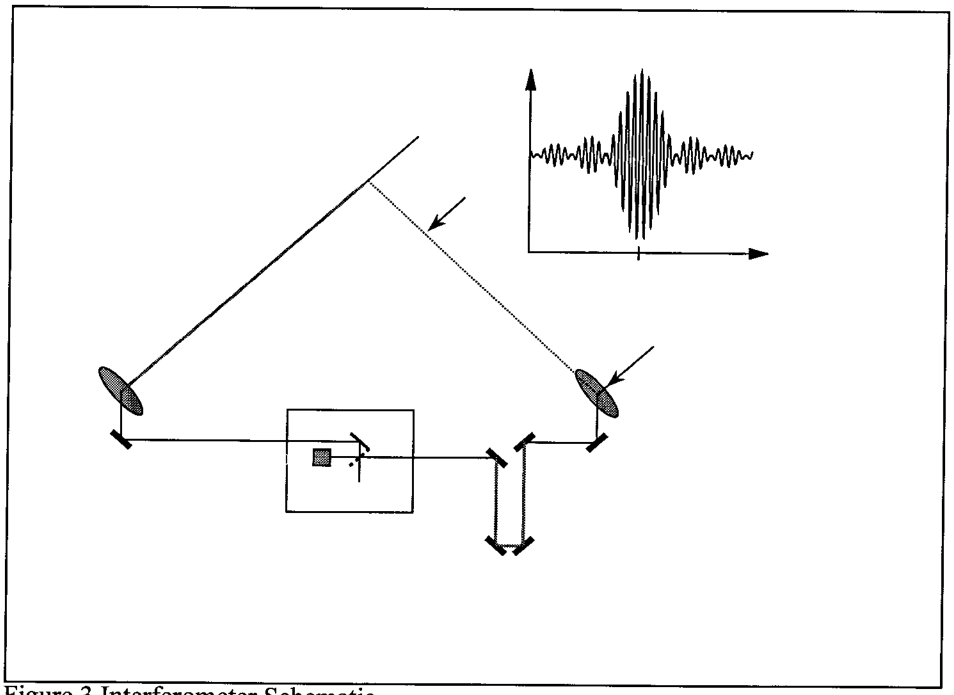


Figure 3 Interferometer Schematic

From the ground, the twin Keck 10m telescopes are being equipped with interferometers to measure angles as small as 20 microarcseconds, leading to a minimum detectable mass in a 1 AU orbit of 66Me for a solar-mass star at 10 pc.

All these are indirect means of detecting planets by observing perturbations to the light or position of the central star. The goal is to see and study the radiation from the planets themselves. Giant planets may be seen from suitably configured ground observatories; but, observatories in space are needed to observe terrestrial sized planets.

Direct Imaging:

To satisfy our basic human curiosity, as well as to achieve a deeper level of scientific understanding, we want to see images of planets around other stars. We want to be able to see the structure of the planetary system, and to use spectroscopic techniques to understand the constituents of the atmospheres of these planets in order to see whether there are biosignatures in evidence, as illustrated in Figure 4 Simulation of Planetary System Image

Doing this requires very high resolution instruments. When viewed from nearest star, the angle from the earth to the sun is about 1 arcsecond, roughly angle made by a dime from a mile away. That's only from about 1 parsec (3.26 light years or 19 trillion miles) away; and we would like to look at stars up to 10 or more parsecs, to the nearest 250 or so stars.

In addition to high resolution, it is also difficult to find the photons from planet while staring into the blinding glare of its star. Earth radiates ~ 1 million times less in the infrared than Sun, and ~ 1 billion times less in the optical spectrum. In addition to brightness, there are considerations of best spectral region to investigate the potential biogenic nature of planetary atmospheres. While there are some weak features in Optical/near-IR (Oxygen A-band, chlorophyll), the broadest, strongest atmospheric signatures of critical bulk and trace gases (CO2, O3, H2O, CH4) are in the mid-IR. This is illustrated in Figure 5 Comparison of "earthshine" in optical vs IR [Ref 9]

Two techniques to deal with this challenge have been under development for some time. Coronagraphs are compact, single aperture systems, but they require precise wavefront control ($\lambda/5000$) and stringent scattered light rejection ($>10^9$). Their difficulties are driven by the need for high resolution which would lead to unrealistically large apertures at longer wavelengths, so the would operate in the optical-near-IR range. They have the advantage of operating warm. Coronagraphs of various configurations and combinations are under consideration, including deformable optics and apodized apertures to accomplish the nulling of the central region of the image.

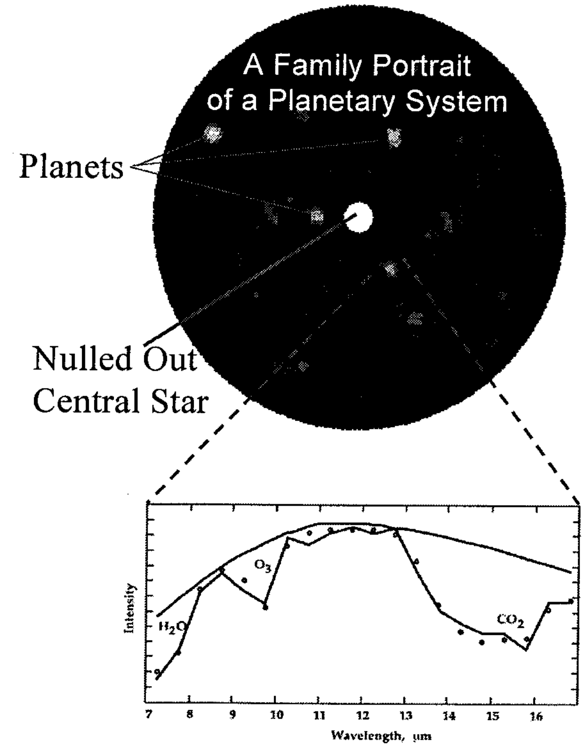


Figure 4 Simulation of Planetary System Image

Interferometry, introduced above, provides another way to accomplish direct imaging through combining the fringe intensity and phase information from many observations of a target with different orientations and length of the interferometer baseline. A nuller is employed to achieve phase cancellation of the light from the central star, thereby allowing the dimmer planets to be observed. The great advantage enjoyed by interferometers is that employing multiple apertures over large baselines (the interferometers equivalent of aperture size), they can achieve the required precision at longer wavelengths. Operating in the 10micron region, they are able to use less precise optics than coronagraphs, and they are able to view some of the more interesting regions of the mid-IR spectrum. Their disadvantage is that they must operate cold, and cryogenic spacecraft have proven to be a difficult and expensive proposition.

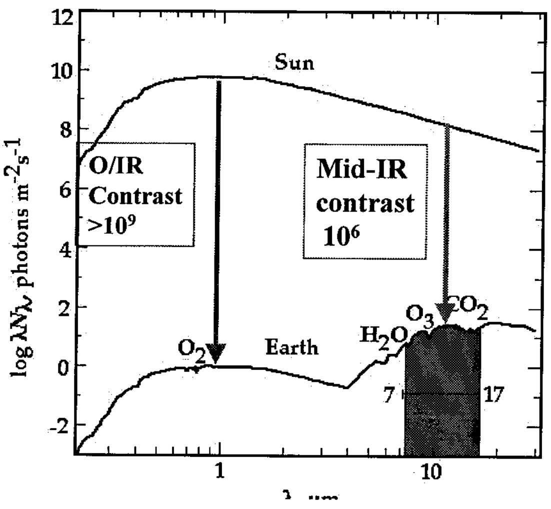


Figure 5 Comparison of "earthshine" in optical vs IR [Ref 9]

4. NASA's PLANET FINDERS

Whereas a very few years ago we did not know whether there were any planets beyond our own solar system, today there is a significant body of knowledge about planets and a large and growing community of planet hunters embarked on a variety of expeditions. Several of the referenced websites have links to a great many of these endeavors ranging from ground-based searches and surveys to proposed and approved space missions in the US and Europe. We will now provide a brief discussion of the main NASA strategic planet finding missions in the Astronomical Search for Origins scientific theme.

Ground Observations

The twin Keck 10m telescopes on Mauna Kea are being linked across their 85m baseline with an interferometer to study exo-zodiacal emissions from potential planet forming regions around other stars. It is also proposed to add 4-6 1.5m outrigger telescopes to fill in UV plane for imaging planetary systems. Because this system will operate for as long as 25 years, it can provide the long duration observations necessary to detect giant planets as large as Uranus on distant (>5AU) long-period orbits, which is an essential part of the census of planetary systems. The first fringes were obtained with the twin Kecks in March 2001. Plans call for the outrigger telescopes to be installed and operational in 2004.

The Large Binocular Telescope consists of a pair of 8m telescopes co-mounted in a binocular configuration. It is being developed by a consortium led by the University of Arizona's Steward Observatory. NASA's Origins theme is providing funding to develop the LBT Interferometer (LBTI) instrument for use on LBT. The LBT interferometer will be constructed in a manner to also take advantage of the LBT's inherent potential for wide-field (Fizeau) interferometric imaging.

It is planned that the interferometer will begin Implementation by late FY 2001 and operation in FY 2004, at which time it will be used to make a Nulling Infra-Red survey of Exo-Systems for TPF (NIREST), of candidate stars. Its purpose is to search for and measure zodiacal dust emission strong enough to compromise future planet imager's performance. A by-product of the survey will be detection of thermal emission from giant exo-planets.

The Interferometry Science Center (ISC) at California Institute of Technology (CIT) will provide standard data formats and the facility for receiving and archiving the science data from LBTI, the Keck Interferometer, as well as future NASA planet finding space missions. The ISC will provide a full spectrum of services to the research community to propose investigations to acquire new data and to access and analyze the body of data acquired as these facilities and missions proceed.

These ground observatories, as well as preceding space missions including the Hubble Space Telescope and the Space Infrared Telescope Facility (SIRTF), which is planned to launch in 2002, will all contribute to a body of scientific knowledge and a community of scientists and technologists to take on the challenge of developing the space missions with the capability to find, image and characterize terrestrial planets.

These precursors which operate in the infrared spectrum will provide all-important characterization of the zodiacal dust clouds around nearby stars. Research will continue to understand the links between these dust clouds and the presence of planets. Also, the potential for these dust clouds to impair the detectability of planets must be understood in order to refine the requirements on the planet finders.

In addition, NASA has and will continue to issue research announcements to solicit concepts for technologies and precursor low-cost missions to bring in new and different possibilities to broaden and deepen the community and its knowledge base.

The Roadmap to a Pale Blue Dot

In order to accomplish the enormously difficult task of imaging terrestrial planets around neighboring stars, NASA and the science community have carefully crafted a roadmap that builds upon the scientific and technical legacy from each mission. This roadmap is illustrated in schematic form in Figure 6 Origins Mission Roadmap

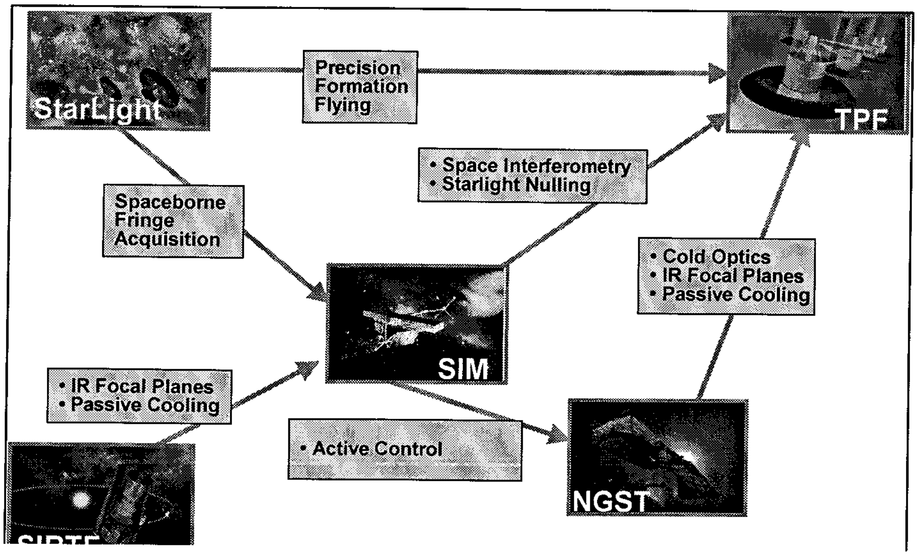


Figure 6 Origins Mission Roadmap

There are key challenges in precision active control of structures to support the precision of the optics and interferometers required. For either the coronagraphic of interferometric architecture for the Terrestrial Planet Finder (TPF) refererred to earlier, about 50 m^2 of aperture is required in order to collect enough photons from either reflected optical light or emitted thermal IR radiation from a planet, while nulling out the blinding radiation from the central star. Therefore light weight large optics robust enough to launch and deploy on orbit (for the single aperture coronagraph) presents significant technical challenge. To achieve the resolution required implies, for the coronagraphs operating in the optical/IR, a very large aperture with precision wavefront control is needed. For the interferometers, an equivalently challenging baseline via either a large deployable precision controlled structure, or a formation of separate spacecraft each with an aperture combined interferometrically must be accomplished.

Flight Missions

The *StarLight* mission is a technology demonstration flight to prove out the techniques involved in operating an interferometer between formation flying spacecraft. StarLight will use GPS-derived technology to provide formation control between the two spacecraft to ~10cm in position and ~4arcmin in angle. Then, the on-board laser metrology system will take over to provide position measures to about 11nm, and control the interferometer delay lines to 35nm. Working over baseline lengths of 30-125m, StarLight will acquire fringes on 5th magnitude stars. StarLight will launch in 2006, in time to provide key data into the final architectural decisions for TPF.

In addition, a number of other future NASA missions need to employ precision formation flying to accomplish their goals, such as far-IR/Submm and X-ray interferometric missions. StarLight is a key technology investment for the future of space astronomy, as their comes a limit to how large an aperture can be launched and deployed. Putting modular apertures on separate spacecraft provides both an extensible and robust approach, providing a measure of resilience even if one of the elements is lost.

The *Space Interferometry Mission (SIM)* is a boom mounted interferometer operating in the optical/NIR. SIM was recommended by the National Research Council decadal survey in 1991 [5] and reaffirmed in 2001 [4]. SIM has selected it's prime contractor (TRW) and brought on board the science team including a dozen leaders in the field of exo-solar planets to help guide the project through it future development. SIM is currently in its formulation phase, applying most efforts to completing the technology developments necessary to accomplish its demanding requirements. It is planned to begin implementation in 2006 for a launch in late 2009.

SIM will provide the exquisite precision and sensitivity needed to detect planets of just a few earth masses in 1-5 AU orbits around stars from 4 to 30 light years. SIM will push the limits on mass of planets around the nearest stars into the range predicted for the rocky as opposed to gas giant planets. SIM will provide 1μas astrometry for narrow angle deep searches, and 4μas for wide angle broad surveys.

Because SIM measures dynamical mass of planets free from the M sin *i* ambiguity of the radial velocity technique, it provides a unique data set. It will enable a rich characterization of multi-planet systems around thousands of stars. Given the statistics from radial velocity searches, this will provide a glimpse into 100s of planetary systems. This is a crucial piece of science, because as of now we know of no systems that resemble our own "grand design" solar system. As discussed earlier, some simulations predict that the kind of systems seen so far would not permit of earths in the habitable zone (HZ), throwing them either into the star or out of the HZ, and not supporting the deposition of necessary volatiles and water. SIM will perhaps find systems with 2-3 earth-mass planets in nice circular orbits in the habitable zone with perhaps gas giants farther out. In any case, from SIM we will get our first census of system structures to develop the "planetary demographics" which future mission will explore.

The *Terrestrial Planet Finder (TPF)* represents the *dénoument* of the "search for new worlds". TPF has been endorsed by NRC decadal survey as their 3rd priority major space initiative, appropriate for a mission which will only formally start development late in the decade. It was said to be "the most ambitious science mission ever attempted by NASA." [4] In addition to imaging planets, TPF will undertake to obtain spectroscopy on their atmosphere to investigate the kinds of spectral signatures that could be indicators of biogenic origin. Again quoting the NRC report, "the discovery of life on another planet is potentially one of the most important scientific advances of this century, let alone this decade, and it would have enormous philosophical implications" [4]

With the kinds of system envisaged, TPF could make observations that would **detect** a planet in 2 hours, **confirm** the planet in 2 days, and **characterize** the planet in 2 weeks. Large optics, cryogenic detectors, precision wavefront control, and either formation flying interferometers or large coronagraphs will present daunting technical challenges.

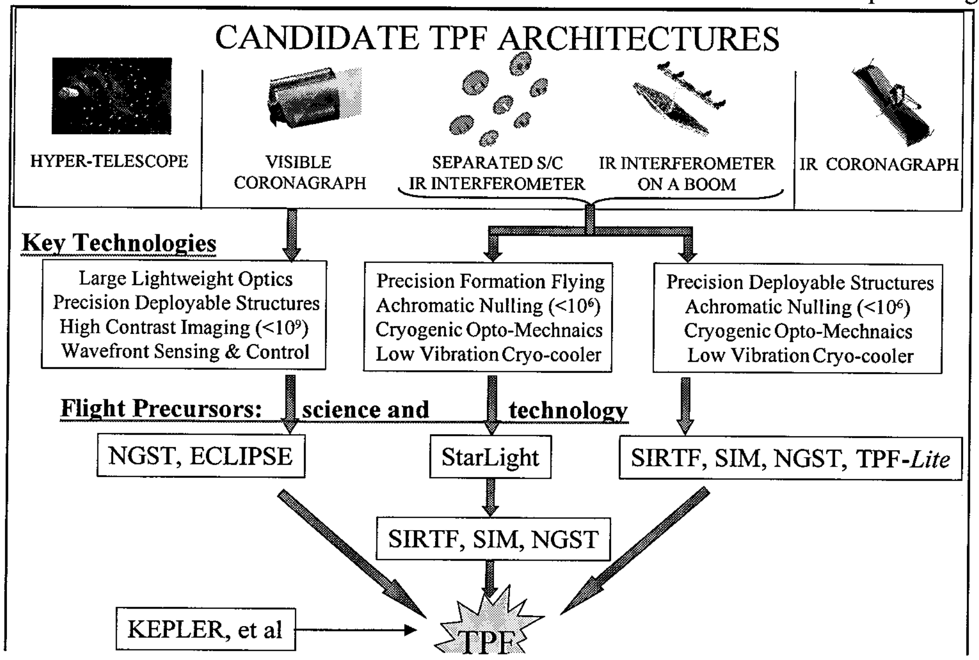


Figure 7 All Roads Lead to TPF*...and Beyond*

To address these challenges, four NASA-sponsored studies involving 16 industrial concerns, 30 universities and 75 scientists have been developing a set of architectural and technological concepts for TPF. In December 2000, four of the most promising of over 20 concepts were selected for further study. (Figure 7) In December 2001, the field is planned (at the time of writing this paper) to be reduced to the two most promising. At that time, the focus will turn to a several year program to bring to readiness the key technologies required for each of the architectures. Some of this work is clearly already in progress, such as the formation flying technology being developed and demonstrated through the StarLight mission. Others, including cryo-coolers, large optics and wavefront control will be put forward for further development. TPF is planned to make a final choice of architecture and a formal new start around 2008, with a launch mid-next decade.

TPF is expected to be able to image planetary systems out for 10s of light years. Starting with systems identified by SIM as most promising, TPF will initially survey and the follow-up with spectroscopic studies to characterize size, orbit, temperature, and chief atmospheric constituents.

5. BEYOND THE HORIZON

Not content to just undertake the incomparably difficult, the science community, in the Origins Roadmap [1], have thrown out a challenge beyond the current horizons of technology. Two missions define this long-term vision of the

Origins program. The first of these is Life Finder (LF), which would follow up on the discoveries of TPF with higher spectral resolution studies needed to identify unambiguously the signs of life on other planets. LF might consist of a TPF-like array of 25-m telescopes, based on technologies developed for other non-planet finding mission in the Origins theme.

The other mission — sometime in the 21st century — is Planet Imager (PI), which could actually spread a number of pixels across the face of a planet around another star, and allow us to look for continents and oceans. We know from the physics that this would require something like a constellation of ~40-m visible-light telescopes operating as an interferometer with a baseline of a few hundred kilometers. Such instruments, while currently almost unimaginably difficult to build and deploy, not to mention beyond the reach of any known funding source, would nonetheless open up a new frontier of exploration unparalled since the first ships navigated in the blind to our new world.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administrations.

6. REFERENCES

[1] *ORIGINS: Roadmap for the Office of Space Science Origins Theme,* JPL Publication 400-887, April 2000.

[2] Geoff Marcy, et al.,
http://exoplanets.org/science.html
http://exoplanets.org/exoplanets_pub.html

[3] Jonathan I. Lunine, "The occurrence of Jovian planets and the habitability of planetary systems" *Proceedings of the National Academy of Sciences, 809-814, vol. 98, no. 3,* January 30, 2001.

[4] *Astronomy and Astrophysics in the New Millennium,* National Research Council, 2001.

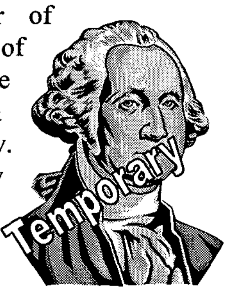
[5] *Astronomy and Astrophysics Survey Committee,* National Research Council, 1991.

[6] William Borucki, *Kepler: A Search for Habitable Planets,* http://www.kepler.arc.nasa.gov/

[7] COROT, http://cfa-www.harvard.edu/planets/corot.html

[8] FAME: Full-sky Astrometric Mapping Explorer, http://www.usno.navy.mil/FAME/

[9 Beichman, et al., *Terrestrial Planet Finder: Origins of Stars, Planets and Life,* May 1999, JPL Publication 99-3. http://tpf.jpl.nasa.gov/



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