NASA'S ASTRONOMICAL SEARCH FOR ORIGINS PROGRAM

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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. In 2002, ASO updated its scientific roadmap, revisiting some of its scientific investigations, and identifying a new class of missions that can help find the answers. Current mission activities and future strategic plans will be surveyed in this talk.

INTRODUCTION

Humanity appears to have always been curious. What, or who, is "out there"? What makes things as they are? Today, 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 daring 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 Objectives[1]:

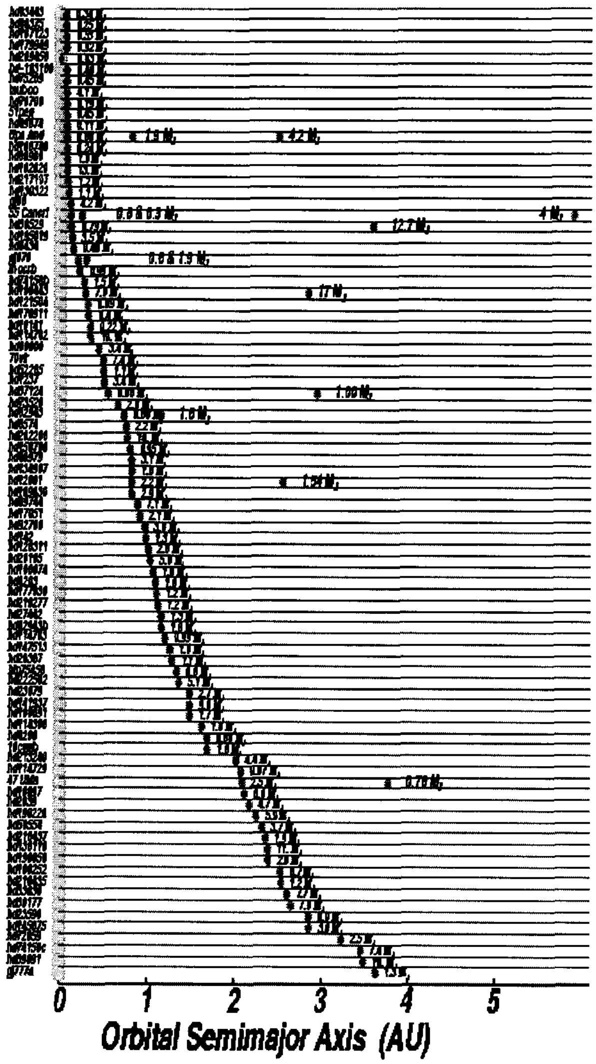
• The Emergence of the Modern Universe: ...to understand how today's universe of galaxies, stars and planets came to be.

• Stars and Planets: ...to learn how stars and planetary systems form and evolve.

• Habitable Planets and Life: ...to explore the diversity of other worlds and search for those that might harbor life.

The first of these goals as well as the star formation and early planet formation part of the second goal are addressed through several ASO missions, including the prolific Hubble Space Telescope, the Space Infrared Telescope Facility (SIRTF), the Stratospheric Observatory for Infrared Astronomy (SOFIA) carried aboard a specially configured Boeing 747 aircraft, and the James Webb Space Telescope (JWST) which plans to launch large ($25m^2$) deployable optics with near- and mid-infrared imaging and spectroscopic instruments in the 2011 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 include the Keck Interferometer on Mauna Kea, the Large Binocular Telescope on Mount Graham, the Space Interferometry Mission, and the Terrestrial Planet Finder.

And, astronomers' vision doesn't stop there, as plans are already being laid for missions decades in the future such as the Single Aperture Far-IR Telescope, an 8-10m telescope that could probe the early and distant star and galaxy formation, and eventually LifeFinder which would employ a set of 25m-class telescopes to search the atmospheres of distant planets for unambiguous tracers of life. The vision is bold.

STATE OF KNOWLEDGE

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, a 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.

Just 5 years ago, we didn't KNOW that there are planets "out there". Today, we have confirmed observations of over 116 planets 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 10% 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 much bigger than earth (0.2 to 15 times the mass of Jupiter, M_J); and most of them are in fast orbits, close to their star (inside 1AU). Is this typical? Is our solar system unusual in lacking these gas giants orbiting in the **habitable zone** (**HZ**: the distance from a star where temperatures are conducive to life by having a temperature that allows liquid water to exist, about 0.01 to 2 AU for stars less than 3 solar masses, M_0)? If there are these close-in giants, what does that mean for smaller rocky planets, like earth, in the habitable zone?

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, where the Doppler-induced shift in wavelength of starlight infers radial motion due to gravitational tugging by the planet. 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.

We know there are a lot of planets. This starts to get at the second Origins Objective. 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. One of the things we want to know is whether there are planetary systems that resemble ours in terms of mass and placement of planets. Most of the giant planets detected so far are very close to the star, are revolving at very high speeds, or are in highly elliptical orbits. Some modeling studies show that these giant planets in these orbits would throw earth-like planets 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". Deeper understanding of how planet-forming environments arise in the course of stellar and galactic evolution is crucial to our understanding. Ground observatories such as the Keck Interferometer and Large Binocular Telescope Interferometer (LBTI) will provide valuable data on the dust environments around stars. Observations by missions such as SIRTF and JWST will provide great insight into these questions. An excellent treatment of the subject and review of related work in the field has been provided by Lunine[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?

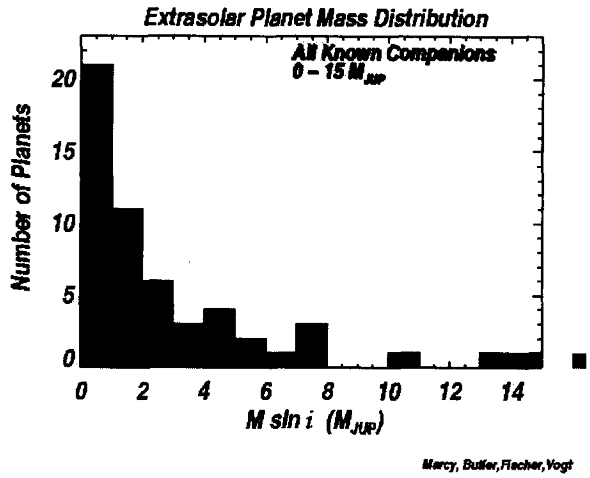


Figure 2 Histogram of Planets as function of apparent mass[2]

PLANET-FINDING TECHNIQUES

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 supported advances in theory, and has led 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.**

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

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 0.5%. 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[6], a mission in NASA's Discovery Program, 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 identifying target stars for these high-powered deep searches.

COROT[7] is a mission approved by the French Space Agency, CNES, dedicated primarily to stellar seismology, but also will study extrasolar planets. It thus provides an alternate source of the important survey information that will be used by the later strategic missions to select targets for deep study. 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.

Eddington is another mission, which has been proposed to the European Space Agency (ESA), which 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

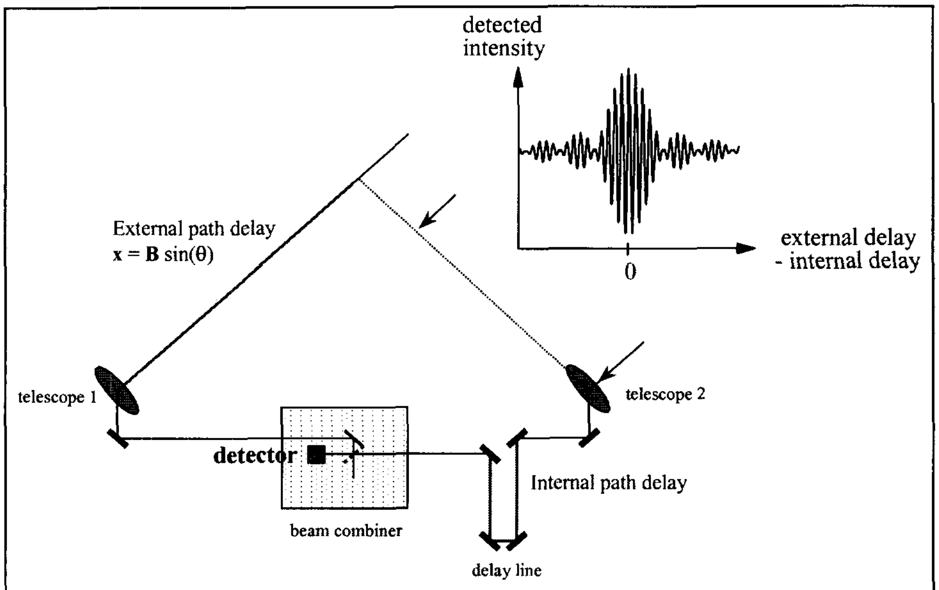
As predicted by Einstein's General Theory of Relativity, an intervening dim star or other mass can amplify the brightness of a background star. Planets orbiting the intervening star can change the amplification in a detectable manner. This provides another technique for photometric detection of planets,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

Astrometry

Astrometry measures the apparent motion of a star due to gravitational influence of a companion as it moves 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.

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.



The peak of the interference pattern occurs when the internal path delay equals the external path delay

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 the nearest star, the angle from the earth to the sun is about 1 arcsecond, roughly the 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 a planet while staring into the blinding glare of its star. Earth radiates ~ 1 million times less in the infrared than the 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

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 (λ/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 they 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.

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 interferometer's equivalent of aperture size), they can achieve the required

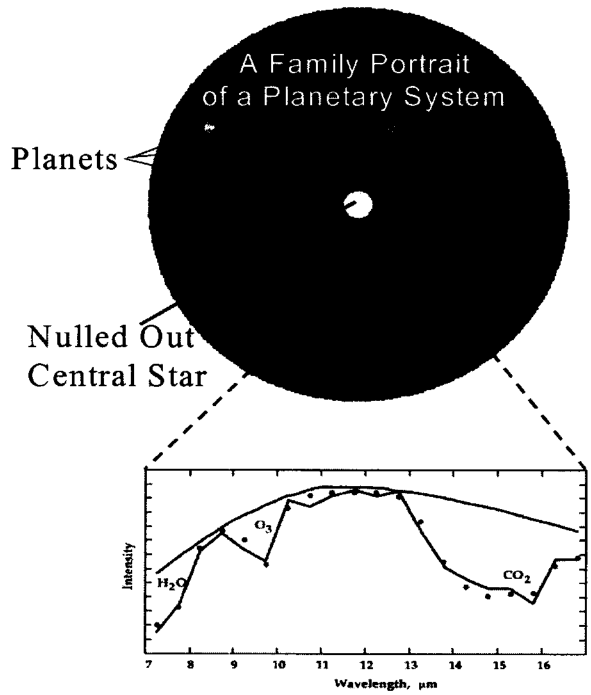


Figure 4, Simulation of Planetary System Image

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.

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 the 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.

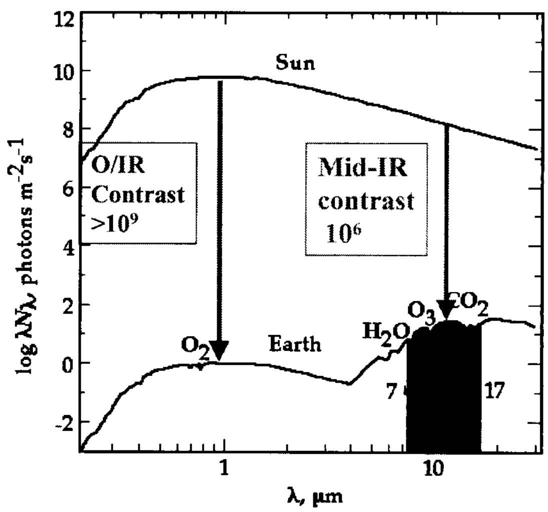


Figure 5, Comparison of "earthshine" in optical vs IR[8]

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.

This system will support the target selection for the Terrestrial Planet Finder (TPF) mission. 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 Michelson Science Center (MSC) 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 MSC 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 launched August 24, 2003, 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.

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.

<u>The Roadmap to a Pale Blue Dot</u>

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 **Error! Reference source not found.**.

There are key challenges in precision active control of structures to support the precision of the optics and interferometers required. For either the coronagraphic or interferometric architecture for the Terrestrial Planet Finder (TPF) referred 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, for the coronagraphs operating in the optical/NIR, 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.

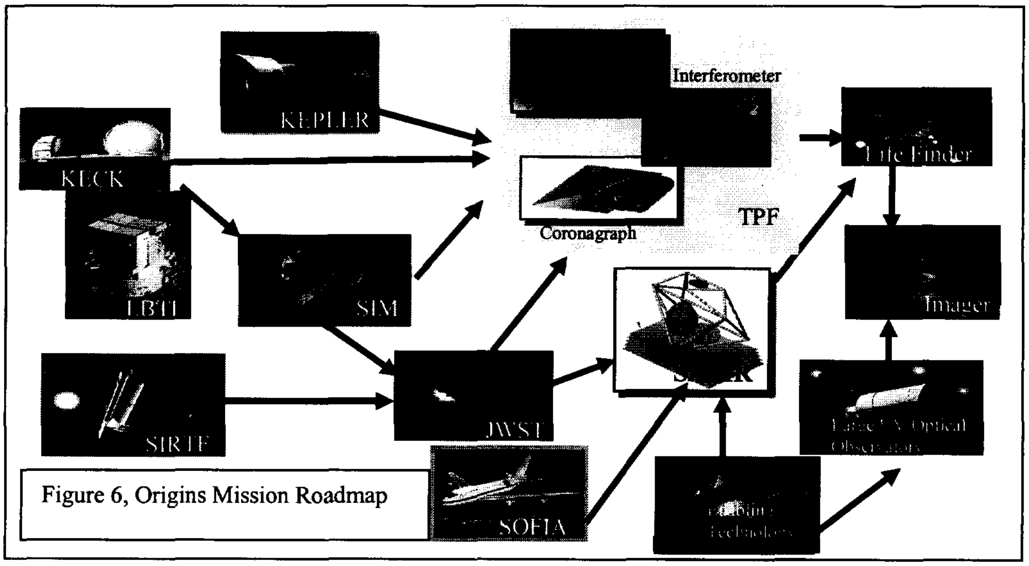


Figure 6, Origins Mission Roadmap

Flight Missions

The *James Webb Space Telescope* mission is the major follow-on to the Hubble Space Telescope in the current mission set. JWST will observe the first stars and galaxies in the Universe. This grand effort is embedded in fundamental questions that have been posed to NASA's Space Science program:

- What is the shape of the Universe?
- How do galaxies evolve?
- How do stars and planetary systems form and interact?
- How did the Universe build up it present elemental/chemical composition?
- What is dark matter?

JWST will observe in the infrared (0.6 to 28 microns) and be capable of seeing objects 400 times fainter than those currently studied with large ground-based observatories, such as Keck or Gemini.

JWST will advance the state of the art for large space telescopes by flying ~6meter deployable aperture, and a sunshade about the size of a tennis court to allow the telescope to cool passively to about 35K. These advances will help pave the way for the large, cold optics required for the Terrestrial Planet Finder.

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 its spacecraft prime contractor (TRW), its instrument contractor (LMMS), and brought on board the science team, including a dozen leaders in the field of exo-solar planets, to help guide the project through its 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 away. SIM will push the limits on the mass of planets around nearby 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. 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" that 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, **detect** an atmosphere 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.

To address these challenges, four NASA-sponsored studies involving 16 industrial concerns, 30 universities and 75 scientists developed 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.**Error! Reference source not found.** In December 2001, the field was reduced to the two most promising classes: interferometers and coronagraphs. A several-year program to bring to readiness the key technologies required for each of the architectures, involving competitive solicitations from academia and from industry is now underway. These technologies include cryo-coolers, large optics and wavefront control. 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 follow-up with spectroscopic studies to characterize size, orbit, temperature, and chief atmospheric constituents.

In the development of the latest Origins Roadmap[1], it was recognized that there are a number of important scientific investigations that could be conducted with more modest scale missions enabled by the technologies being spun off by the major Origins strategic missions. Some of these have already been proposed through the Discovery and Explorer programs. Others would require a larger resource commitment, but still compatible with a competed mission management model. The Roadmap recommended a new initiative for *Origins Probes*, missions of the $500M class which could be competed in the community for leadership by key scientists with implementation support from the NASA flight centers. Programmatic groundwork is being laid to develop mission concepts for Origins Probes, and to explore possible funding in future years.

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 missions in the Origins theme. A mid-step toward LF may be realized in the Decadal Survey-recommended Single Aperture Far-Infrared Observatory (SAFIR) which would fly a ~10m aperture and employ advanced detectors to pursue difficult astrophysical questions, as well as provide the ability to conduct life-finding investigations on many of the nearer stars.

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 unparalleled 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.

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