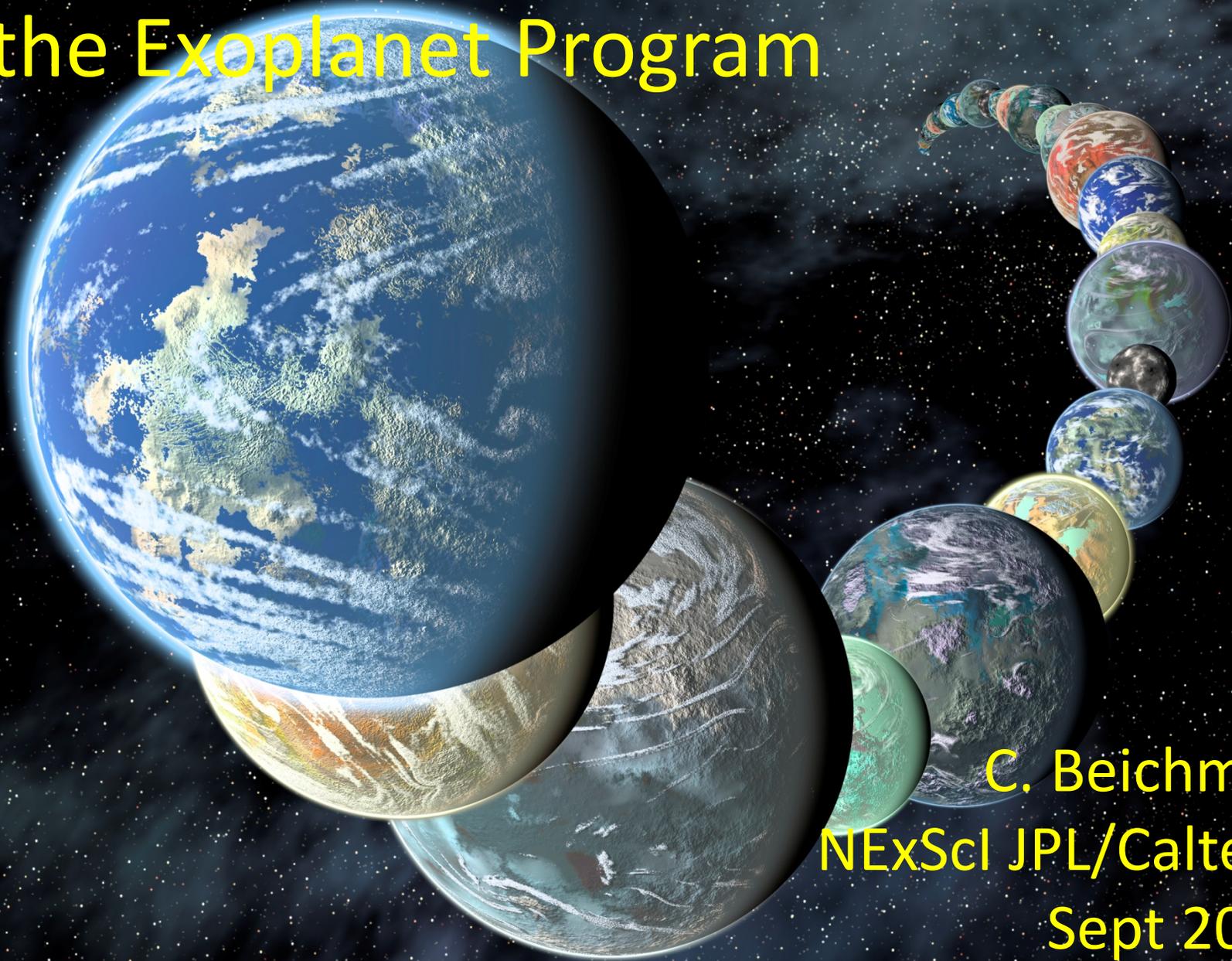


Some Thoughts on the Origins of the Exoplanet Program



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1980s and Early 1990s

First Tentative Steps Toward Exoplanets

- Campbell and Walker (1988) develop PRV using a HF cell but find no planets. Unlucky but consistent with their sensitivity and exoplanet demographics. (Important lesson on yield for Habex/LUVOIR)

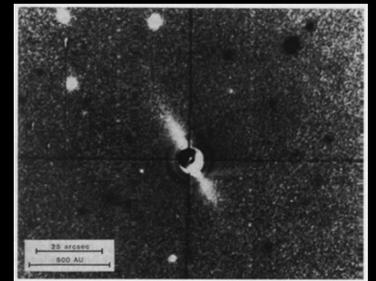
- “14 stars are virtually constant in velocity, showing no changes larger than about 50 m/s....
- “Seven stars show small, but statistically significant, long-term trends in the relative velocities....
- “Companions of about 1-9 Jupiter masses are inferred...
- “These low-mass objects could represent the tip of the planetary mass spectrum...
- “Observations are continuing to confirm these variations, and to determine periods.”

- IRAS discovers debris disks with obvious links to planetary systems. Smith and Terrile (1984) make a direct visible image.

- Latham et al (1989 Nature 339, 38) discover first true exoplanet but call it a brown dwarf

- “The unseen companion of HD114762 - A probable brown dwarf “ based on RV observations which is now accepted as the first true exoplanet (~10 Mjup Planet)

- Aleksander Wolszczan (1992) discovers an exoplanet system orbiting a pulsar. Proves that making planets must be pretty easy, but otherwise not very relevant! Becomes only the second astronomer to get a stamp in Poland. The other was Copernicus



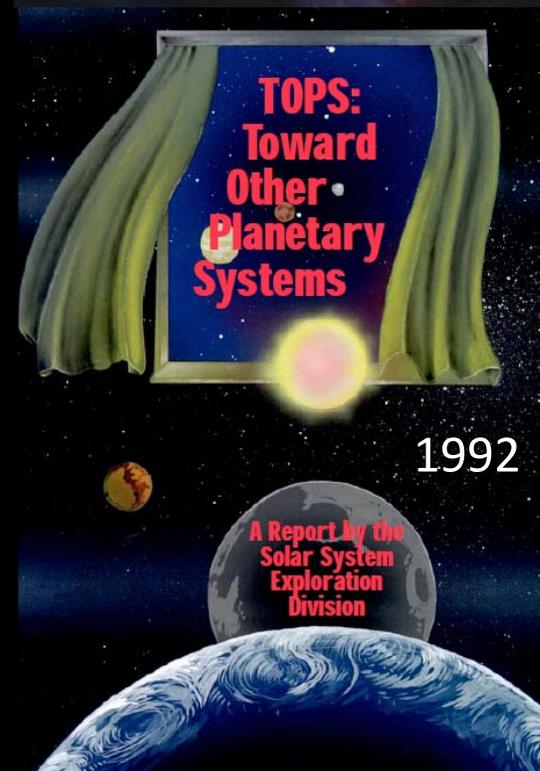
NASA Beginnings (1980-1995)

- Project Orion (1980) examined a shaped pupil to control diffraction to search for exoplanets
- Discovery of β Pictoris disk led to internal JPL studies of the Circumstellar Imaging Telescope which was shelved for lack of technology readiness of deformable mirrors. Shifted to astrometry \rightarrow SIM
- Exoplanet Science at NASA emphasized in the Solar System Division which initiated the TOPS program (*Toward Other Planetary Systems*) even before the discovery of exoplanets!
 - “The first phase of the TOPS Program ... is centered on a ground-based observing program.”
 - “Discover and study planets with masses as low as those of Uranus and Neptune around 100 or more stars in the solar neighborhood.”
 - “The defining element of TOPS-0 is the Keck II telescope...”
 1. Telescope construction
 2. Enhance image sharpness (AO)
 3. Focal plane instrumentation for studying planetary phenomena and materials around other stars (HIRES and AO)
 4. An interferometer project using the Keck telescopes [for planet detection via astrometry with 4-6 outriggers]”

PROJECT ORION

A Design Study of a System for Detecting Extrasolar Planets

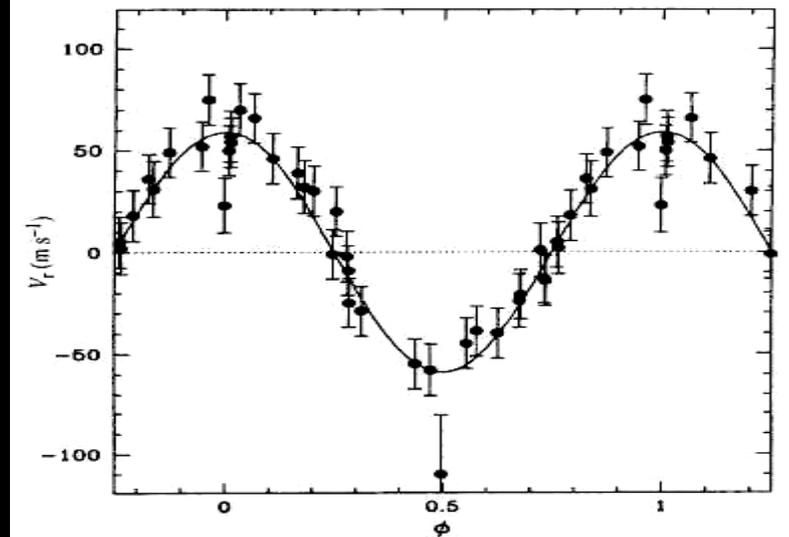
1980



The “Annus Mirabilis” of Exoplanet Science --- 1995

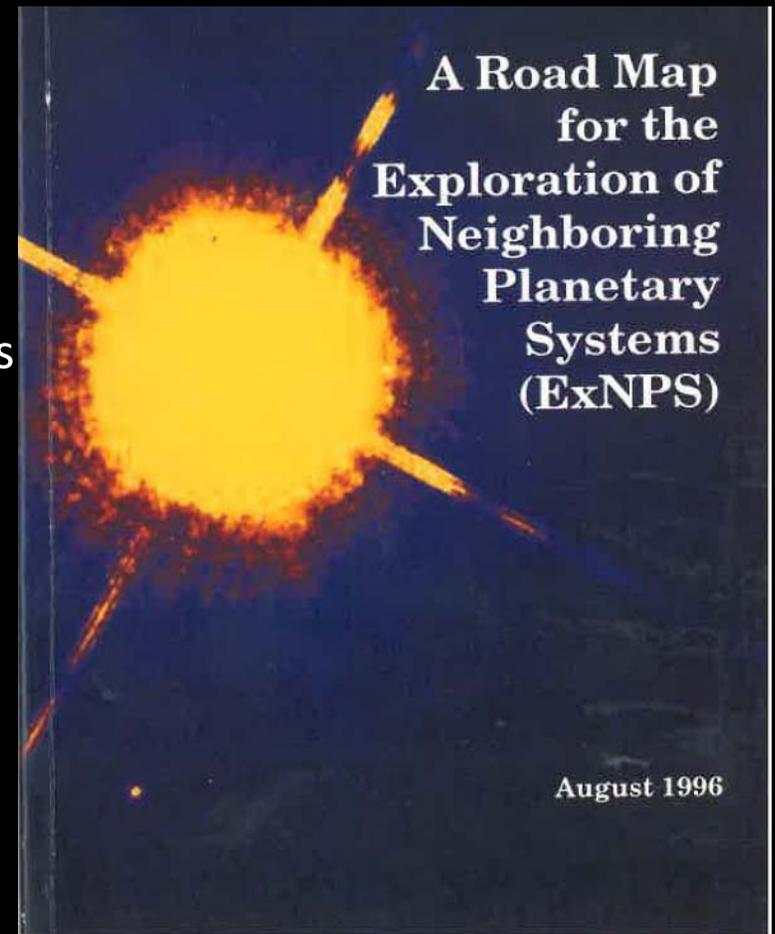
- Two dramatic results made 1995 the miraculous year (“annus mirabilis”) which helped to create NASA’s exoplanet program
- David McKay (JSC, not Chris McKay of Ames) claimed Allen Hills meteorite ALH84001 contained fossil bacteria
- Discovery and subsequent confirmation of a “Hot Jupiter” orbiting the main sequence star 51 Peg (Mayor and Queloz; Marcy and Butler)
- The Clinton Administration acted with enthusiasm and asked NASA and NSF to propose with initiatives. NASA developed the Origins program in response. NSF went to sleep, as usual.

Bill Clinton's spin doctor, Dick Morris, leaked the Mars Rock story to a \$200-an-hour call girl



Exploration of Neighboring Planetary Systems (EXNPS)

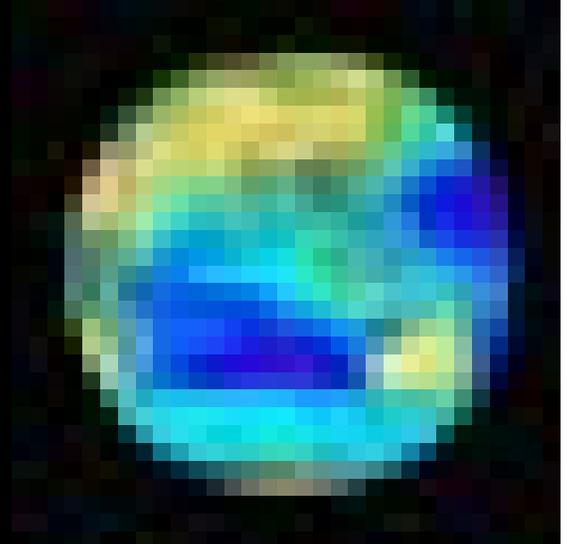
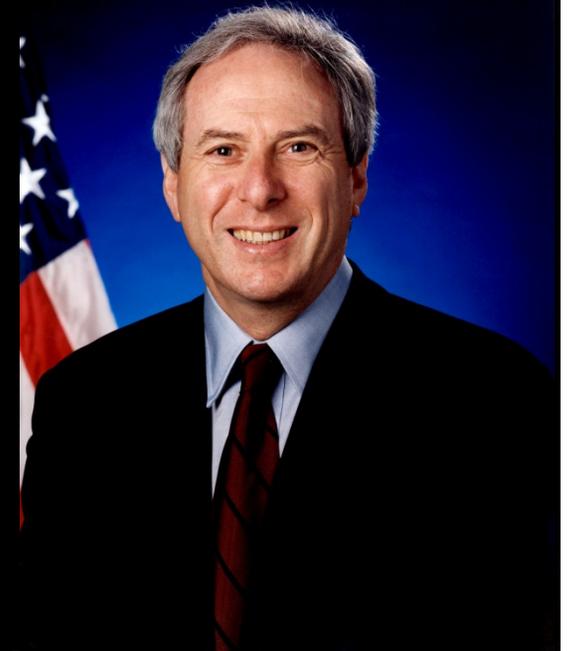
- NASA Astrophysics already studying exoplanet missions when the floodgates opened with discovery of 51 Peg and many more RV planets
- On-going Exploration of Neighboring Planetary Systems (EXNPS) study initiated by Elachi with broad community involvement (C. Beichman was study lead)
- Report called for broad program to find and characterize other Earths
 - An IR nulling interferometer (TPF) based on designs from Roger Angel & Nick Woolf (UofA), Alan Leger (Paris), Mike Shao
 - Acceleration of missions from 1990s Decadal Report: SIRTf and SIM
 - Strong precursor program of ground-based science including enhancement of Keck HIRES spectrometer, development of the Keck Interferometer
 - Recognized importance of microlensing, transits and biomarkers, exozodi on the road to TPF



After review by Blue Ribbon panel chaired by Charles Townes, NASA accepted many of these recommendations, reversing decline in the Astrophysics budget. JWST studies were initiated.

2000-2010: A Period of Great Dreams

- NASA Administrator Dan Goldin deserves credit for making exoplanets a NASA goal
 - Wanted resolved images of other planets requiring a flotilla of Keck telescopes working as a giant space interferometer
- NASA Astrophysics (Wes Huntress) pursued three (realistic) exoplanet programs.
 - Space Interferometer Mission (SIM) --- find HZ earths via sub-micro-arcsecond astrometry
 - Terrestrial Planet Finder (TPF) -- image Earths and look for biomarkers with 10 μm nulling interferometer or 8 m visible coronagraph
 - NGST --- an 8-m, 1-5 μm replacement for HST
 - Increased funding allowed start of Decadal recommended SIRTF \rightarrow Spitzer



The Origins Program

- Firouz Naderi and CAB initiated the Origins program (1996) for NASA Astrophysics with responsibility for planet finding activities, incl TPF-I, SIM, and the Keck Interferometer, along with associated technology development programs.
- SIM Phase A with extensive technology program and selection of science team.
- TPF-I (Interferometer) studies go ahead with formation flying and structurally connected designs. Close collaboration with ESA on their Darwin project
- TPF-C (Coronagraph) was added as a second option along with TPF-I
- TPF-O (Occulter) A simple starshade (spherical balloon) rejected for insufficient stellar rejection. Alternative shapes based on innovative coronagraphic masks would later bring back this concept
- Starlight project initiated as formation flying and interferometry precursor
- Keck Interferometer developed. Outriggers cancelled due to protests about environmental and spiritual damage to Mauna Kea. Keck-Keck interferometer had first light (2003) and made EZ survey at 100 Zodi level, LBTI pursued in parallel for <10 Zodi measurements
- Interferometry Science Center (ISC) at IPAC established as Science Operations Center for SIM, Keck, (eventually TPF) → Michelson Science Center → NASA Exoplanet Science Institute

Origins → Navigator Program

- Mike Devirian takes over from Naderi as Program Manager in 2000. Program is renamed Navigator with mission definition and technology for SIM, TPF, Keck, LBT
- President G.W. Bush's Vision for Space (2004, post Columbia loss) includes a call to "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars."
 - TPF-C: Study for 4-6 m coronagraph goes ahead for planned launch in 2104., 10-12 m coronagraph study is cancelled.
 - TPF-I: Study for formation flying interferometer goes ahead with ESA for Launch in 2020+. Structurally connected interferometer study is cancelled.
- Work focused on decadal endorsements for SIM & TPF, Probes
- Wes Traub takes over as Program Scientist (2005) after CAB returns to campus to take over NExSci
- Navigator Program → Exoplanet Exploration Program (2008)

TPF and Decadal Reviews

2000 Decadal Review---“A truly revolutionary and ambitious mission, the Terrestrial Planet Finder (TPF) ...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”

2010 Decadal Review---“The culmination of the quest for nearby, habitable planets is a dedicated space mission... It is too early to determine what the design of that space mission should be...It is not even clear whether searches are best carried out at infrared, optical, or even ultraviolet wavelengths.”

2020 Decadal Review---“The Committee endorses (Habex | LUVOIR | LISA | FarIR Surveyor | WFIRST Starshade Rendezvous)...”



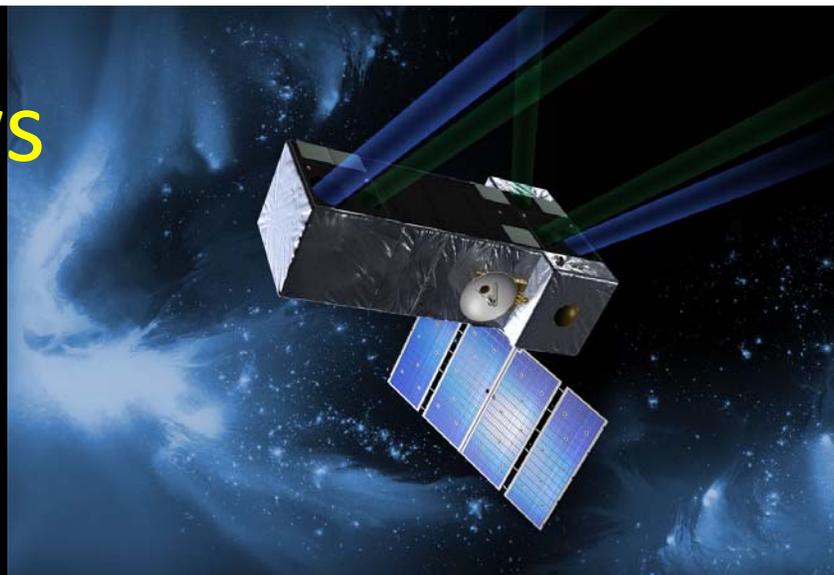
SIM and Decadal Reviews

1990 Decadal Review: “The Astrometric Interferometric Mission (AIM) would permit definitive searches for planets around stars as far away as 500 light-years through the wobbles of the parent star”

2000 Decadal review: “Endors[es] the completion of the Astrometric Interferometry Mission”

2010 Decadal Review: 20 years and \$500M later, death by footnote:

“SIM [does] is not included in the recommended program for the decade, following the committee’s consideration of the strengths of competing compelling scientific opportunities and the highly constrained budget scenarios described in this report.”



SIM: Overtaken by Events

- Improving RV performance
- European GAIA mission with stronger astrophysics program
- Strong community desire for general purpose JWST

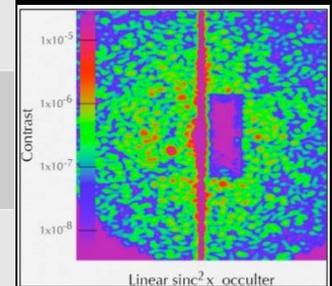
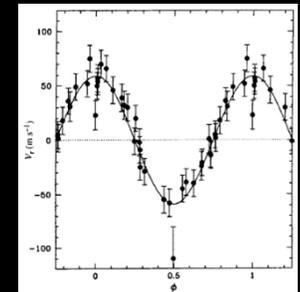
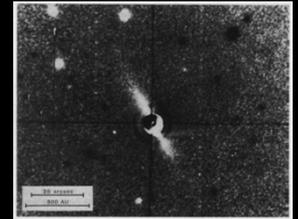
Recent History

- SIM is cancelled after 2010 decadal review. Probes go nowhere. WFIRST goes ahead with emphasis on Dark Energy and microlensing
- Kepler is launched in 2009 and revolutionizes exoplanet research. Bill Borucki deserves enormous credit for his vision and perseverance
- Gary Blackwood takes over as ExEp Program Manager in 2013 with Wes Traub continuing as Program Scientist
- Karl Stapelfeldt is brought in as Program Chief Scientist
- WFIRST receives life-giving boost with donation of NRO 2.4m telescope and addition of technology demonstration coronagraph

Year	Exoplanet Milestones
1984	IRAS discovers debris disks and first visible image of disks
1989	Latham Discovery of first exoplanet/brown dwarf by Latham
1994	Pulsar Planet discovered by Wolszczan
1995	Discovery of 51 Peg (Mayor and Queloz) starts RV exoplanet revolution
1996	EXNPS report submitted to NASA and initiation of NASA's Exoplanet Program
1999	First ground-based transit measurement of HD 209458B
2000	Decadal review endorses SIM, TPF technology, starts JWST
2002	First exoplanet spectrum in transit (Charbonneau)
2003	Spitzer launch for extensive Exozodi science. Keck Interferometer first light
2004	First microlensing planet discovered by OGLE team
2005	Spitzer detects mid-IR from eclipsing exoplanet; imaging of 2MASS 1207b
2008/9	First imaged planets HR 8799 and beta Pic
2010	Decadal review cancels SIM, starts WFIRST, endorses coronagraph tech demo
2010	Kepler launched initiating transit revolution
2013	ESA's GAIA launched for astrometry observations, including gas giant survey
2013	TESS selected as all-sky transit survey mission for launch in late 2017
2014	K2 mission begins after failure of 2 nd Kepler reaction wheel

Terrestrial Planet Finder Study Milestones

1984	beta Pic: first high contrast image of an exoplanetary system (Smith & Terrile)
to 1988	JPL Circumstellar Imaging Telescope study
1990	Analysis of HST optics shows contrast for exoplanets not achievable (Brown & Burrows)
1989-1995	JPL Astrometric Imaging Telescope study leads to Space Interferometry Mission
1997	Thermal infrared interferometry mission concept (Angel & Woolf) for Terrestrial Planet Finder
2000	Decadal survey endorses TPF tech development
2001/2	TPF studies produce coronagraph option
2004	Vision for Space Exploration leads to well-funded TPF-C mission study, STDT & design effort
2006	Study report completed, project shelved, TPF
2010	Decadal survey endorses New Worlds tech development for a habitable exoplanet mission



Some Key People

Programmatic

Goldin, Elachi, Devirian, Coulter, Blackwood, Beichman

RV Science

Marcy, Butler, Latham, Fischer, Mahadevan, Howard

Transit Science

Borucki, Charbonneau, Latham, Seager, Deming, Knutson

Imaging Science

Macintosh, Traub, Spergel, Kasdin, Stapelfeldt, Trauger, Mawet

Interferometry (RIP)

Angel, Shao, Leger, Hinz, Colavita

Microlensing

Gould, Bennett, Gaudi, Yee

ExoZodi

Beichman, Hinz, Stapelfeldt, Rieke, Su, Bryden

Some Key Lessons

- SIM cancellation
 - Refusal to simplify and focus early on unique science leads to long delays which can lead to erosion of key science goals, e.g. improved PRV and GAIA mission
 - Science yield important if measurement capability is close to demographic boundary
- Poor community relations
 - Focus on long term goal of finding Earths blinded program to more near term opportunities, especially transits and transit spectroscopy
 - Little support of near term science, e.g. ground-based, although not really our fault
 - Program seen as unresponsive and irrelevant to most exoplanet scientists
 - Not enough funding going outside of JPL (NASA) to university community for technology or science
- Long delays in achieving an imaging mission
 - Fundamental technology challenges have led to changing designs over decades, TPF-I→TPF-C→TPF-O, with (still) no clear winner in sight
 - Science bar continually raised as ground based science grabs low hanging fruit
 - Community wants mission with broad astrophysics science capability, not a highly specialized, very expensive planet finder.
 - Need strong political support