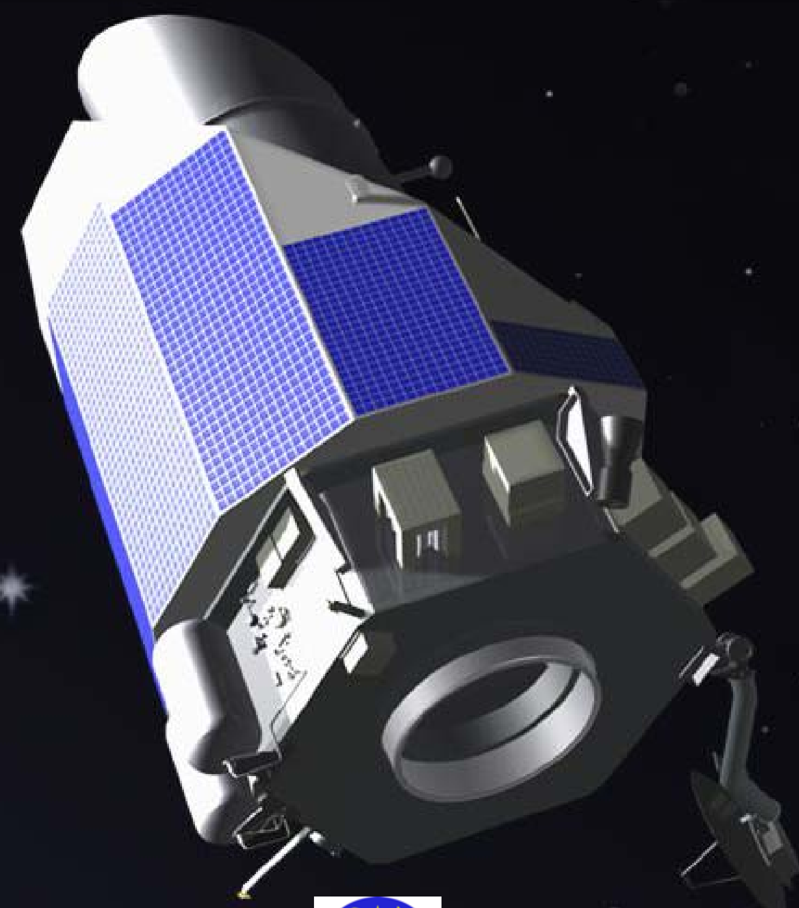
Transformation of a Great Science Idea to Mission Hardware

W. J. Borucki, NASA Ames
& the Kepler Team



Ames Research Center
Ball
LASP
JPL
LHS
SAO
SETI Institute
STScI

OUTLINE

A Search for Habitable Planets

1. Getting the mission selected
2. Overview of the Kepler Mission
3. Mission development
4. Analysis of the results
5. Community participation

1. GETTING THE MISSION SELECTED

Types of Missions & advocacy

- Institution vs. PI-led
- Institution chooses team vs PI chooses team

PI Mission lines; Explorer, Discovery, New Frontier

Announcement of Opportunity

Proposals & reviews;

- Improve proposals & resubmit

Demonstrate: Important science, team capability, technical readiness, realism of cost

Concept Study Report & reviews & selection

REVIEW PANELS, SELECTION OFFICIALS, & HQ OVERSIGHT

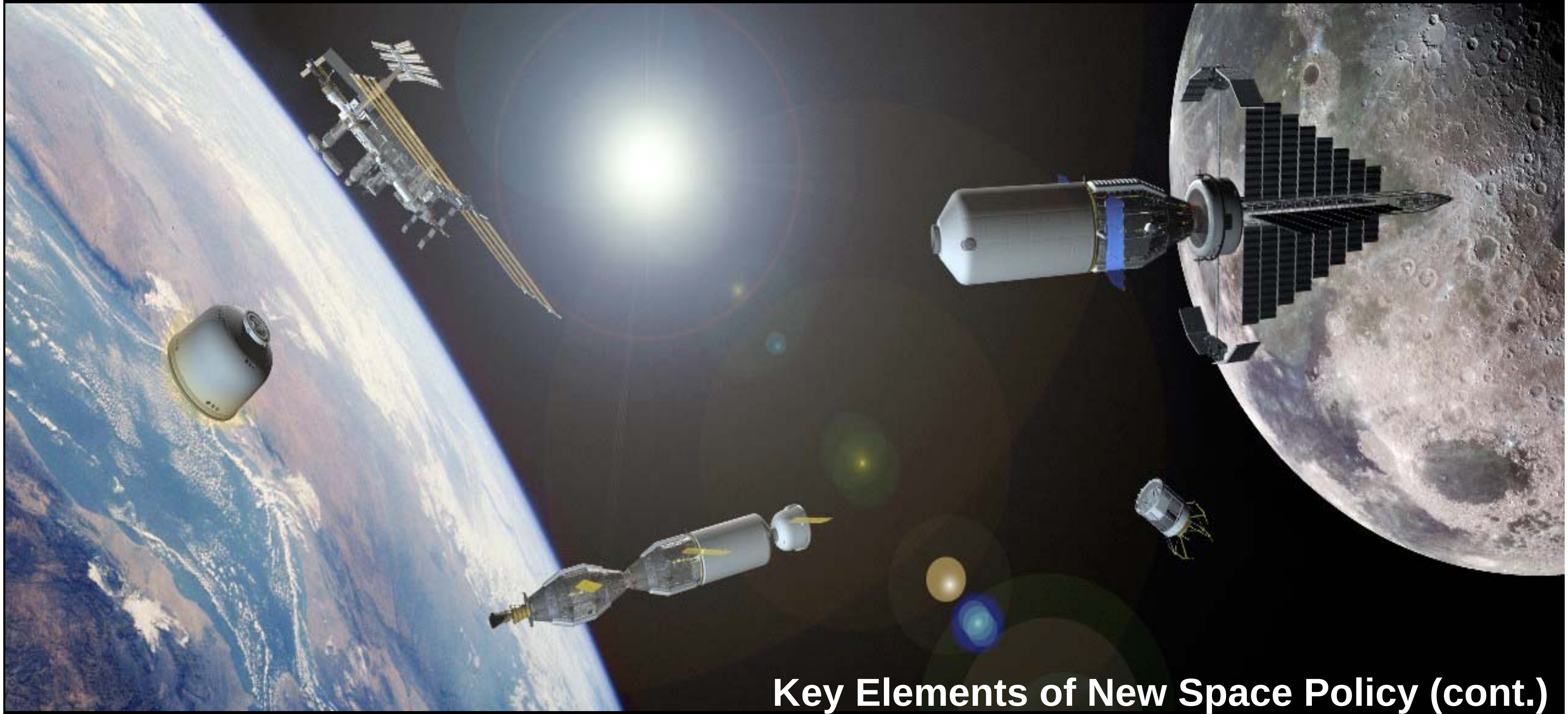
Kepler
A Search for Habitable Planets

- 30 responsive proposals rcvd; 25 for full missions
- Review panels & selection officials fund Phase A studies of 3 full missions and 2 "missions of opportunity"; $250K & 4 months to each full mission.
- Panels rank on science, technical readiness, team capability, education & public outreach plan, management plan, realism of cost plan
- Review panels for mission development
  - Independent Review Team → appointed by HQ or DPO
  - Standing Review Team → Same grp of individs appt by Center management
- Selection officials: Associate Administrator for Space Science
- HQ oversight
  - Colleen Hartman (Solar System Exploration Office)/Anne Kinney (Origins Program Office) appoints Program Executive & Program Scientist
  - Continuous oversight & support by Discovery Program Office (DPO)

New Space Exploration Vision

"This cause of exploration and discovery is not an option we choose;

it is a desire written in the human heart." – President Bush



Key Elements of New Space Policy (cont.)

Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. 01/22/2004

GUIDANCE FROM NASA STRATEGIC PLAN

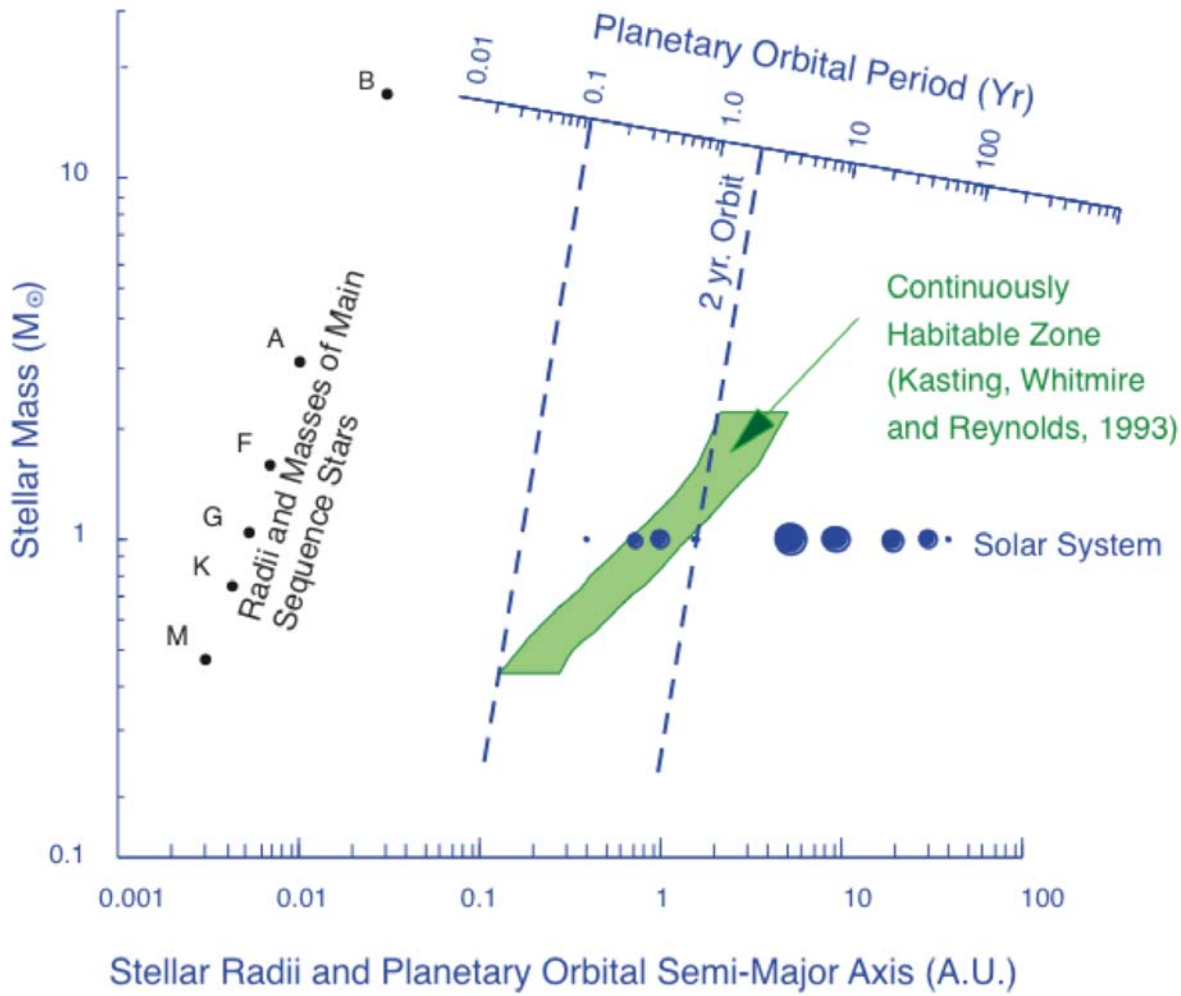
A Search for Habitable Planets

- Strategic Goal 3: Develop a balanced overall program of science, exploration, and aeronautics consistent with the redirection human spaceflight program focus on exploration.

- Sub-goal 3D: Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets.

The Terrestrial Accretion Zone and The Habitable Zone for Various Stellar Types

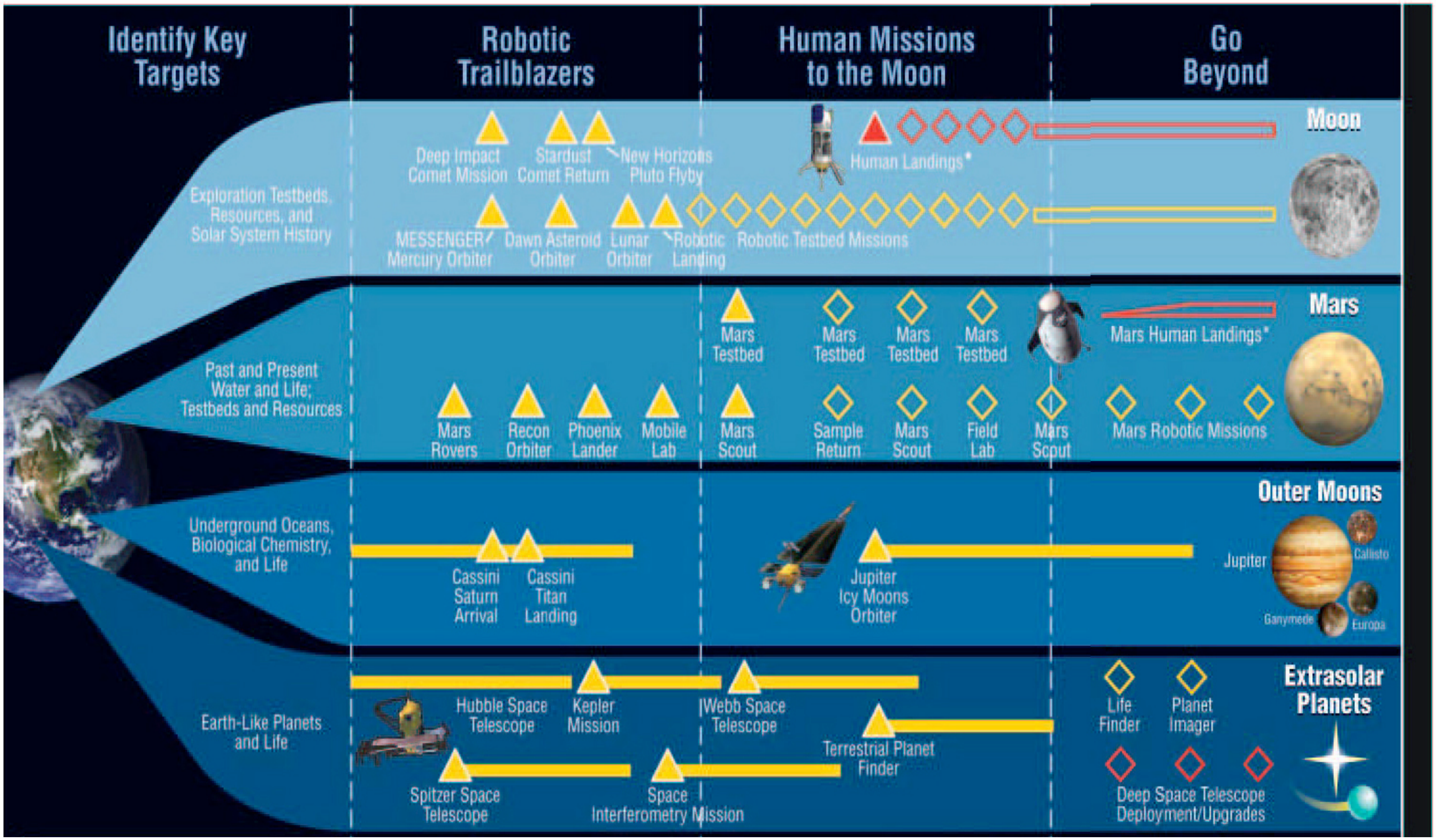
Kepler
A Search for Habitable Planets



Kepler: A Discovery Mission to Determine the Frequency of Earth-size Planets in the HZ

Kepler

A Search for Habitable Planets



CAPABILITIES OF THE SCIENCE TEAM

A Search for Habitable Planets

William J. Borucki, PI, and David Koch, Deputy PI

Stellar Occultations & High-Precision CCD Photometry

- Timothy Brown, Los Cumbres Obs.
- Edward Dunham, Lowell Obs.
- John Geary, SAO
- Ronald Gilliland, STScI
- Steve Howell, U. Ariz
- Jon M. Jenkins, SETI Institute

Doppler Velocity Planet Searches

- William Cochran, UTexas
- David Latham, SAO
- Geoff Marcy, U. Cal., Berkeley

Stellar Variability

- Gibor Basri, U. Cal., Berkeley
- Joergen Christensen-Dalsgaard, Denmark
- Andrea Dupree, SAO
- Dmiter Sasselov, Harvard

Theoretical Studies

- Jack Lissauer, NASA Ames
- Alan Boss, Carneige Institute Wash.

Mission Operations

- Donald Brownlee, U. of Washington
- Nick Gautier, JPL
- Yoji Kondo, NASA GSGC

General Overview

- John Caldwell, York U.
- David Morrison, NASA Ames
- Tobias Owen, U of Hawaii
- Harold Reitsema, Ball Aerospace Co.
- Jill Tarter, SETI Institute

Education and Public Outreach

- Edna DeVore, SETI Institute
- Alan Gould, Lawrence Hall of Science

TECHNICAL READINESS: PROOF THAT AUTOMATED PHOTOMETRY OF THOUSANDS OF STARS IS POSSIBLE

A Search for Habitable Planets

Vulcan transit search of 10,000 stars for extrasolar planets

- **OBJECTIVES:**
- Monitor 10,000 stars continuousl for periods of at least 6 weeks
- Detect jovian-size planets in sho period orbits
- Use Doppler-velocity measurements to determine mass and density
- **TELESCOPE:**
- Aperture: 10 cm
- Focal length: 30 cm
- Field of View: 7x 7 degrees
- Detector: 4096x4096 CCD with 9 μ pixels

TESTBED REQUIREMENTS TO DEMONSTRATE CAPABILITY

Kepler
A Search for Habitable Planets

There are many confounding factors that influence the system noise and hence the detectability of transits. The purpose of the tests is to measure the effects of these factors, identify the optimal operating conditions under the influence of each factor and show that when all of the effects are taken together Earth-size transits can be reliably observed. The Test Facility incorporates the ability to measure the following effects:

1.Spacecraft jitter:	Motion to 500 millipixels each axis (expect ±3 millipixels)
2. Dynamic range:	Target stars m_v=9 to 14. Background stars to m_v=19
3. Double stars:	Five magnitudes fainter at 0.5 to 5 FWHM separation
4. Smearing:	Shutterless readout with other stars in the same column
5. Field rotation:	Star field moved to different portions of CCD
6. Temperature:	CCD operating range from -60°C to –40°C
7. Focus change:	Effects of focus variations on noise, psf and plate scale
8. Optimal aperture:	Operate from 3 to 11 pixel (binned) photometric aperture
9. Thermal effects:	Various effects, such as, differential expansion
10. Bright stars:	Effects of blooming caused by m_v=4 star
11. Cosmic rays:	Effects of cosmic-ray hits on the CCD

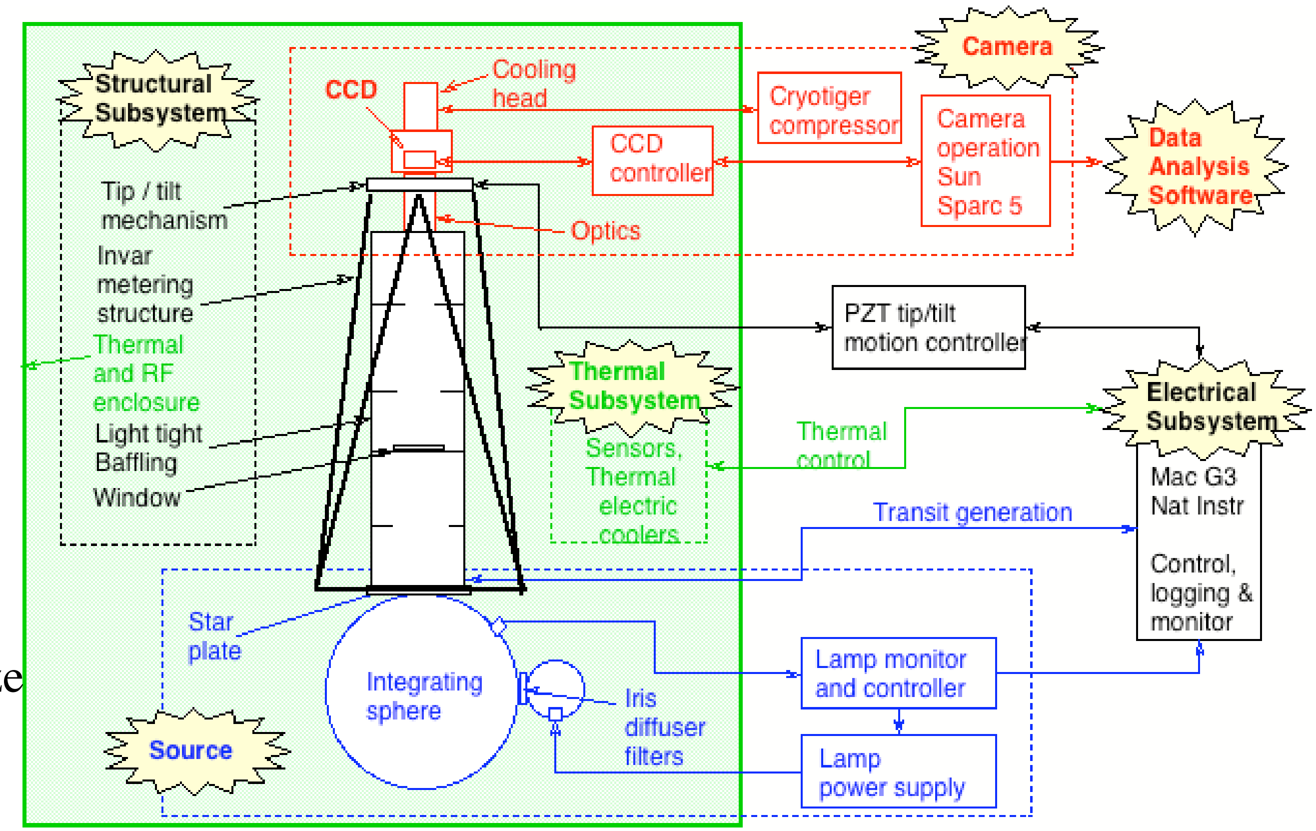
CCD TESTED

For these tests an EEV 42-80 back-illuminated CCD was selected. The CCD has 2048x4096 pixels of 13.5 μm. The overall size is 27x54mm. The pixels are binned on the CCD to 27μm. In effect it is being used as a 1024x2048 device. The binning improves both the readout speed and the photometric precision. The device is read out at 1 megapixel/sec.

Testbed Facility Description

Kepler
A Search for Habitable Planets

Source: simulates the sky and produces;
- Same flux as for m_v = 9-19 stars
- Similar spectral colors as the Sun
- Same star density for mv < 19
- Several bright stars, mv =4
- Generation of Earth-size transits



Baseline measurements show that the average system noise is below the required noise limit to detect Earth-size planets for mv=12 stars and 3.5 Earth-area at mv=14 at 4σ for a single transit.

OPERATIONS ORGANIZATION

A Search for Habitable Planets

Science Ops Center - Ames

- Scientific direction
- Select target stars
- Manage Instrument
- Diff. ensemble photometry
- Stellar light curves
- Transit search
- Candidate planet list
- Direct follow-up observing
- Final planet determination

Flight Planning Center - Ball Aerospace

- Manage MOC
- Ensure spacecraft health/safety
- Anomaly resolution for Flight Seg.

Observ-ing request

Stellar data

Complementary Observing - SAO/UT/UC-B

- Stellar classification
- Elim. false positives
  - low resolution spectroscopy
- Stellar properties
- Giant planet mass
  - high resolution spectroscopy

Mission Ops Center - LASP

- Cmd/control spacecraft
- DSN scheduling
- Acquire all data
- Engr. data archive
- Anomaly response

Target list

Calibrated data

Results

Raw data

Data Management Center - STScI

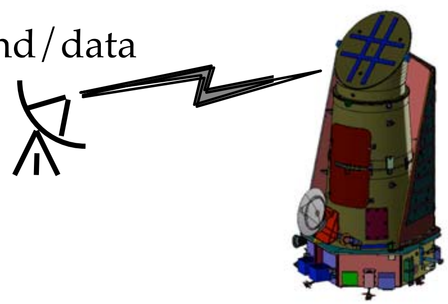
- Calibrate data
- Archive data
- Difference images
- HST follow-up

Education Public Outreach - LHS/SETI

- Formal education
- Informal education
- Public outreach

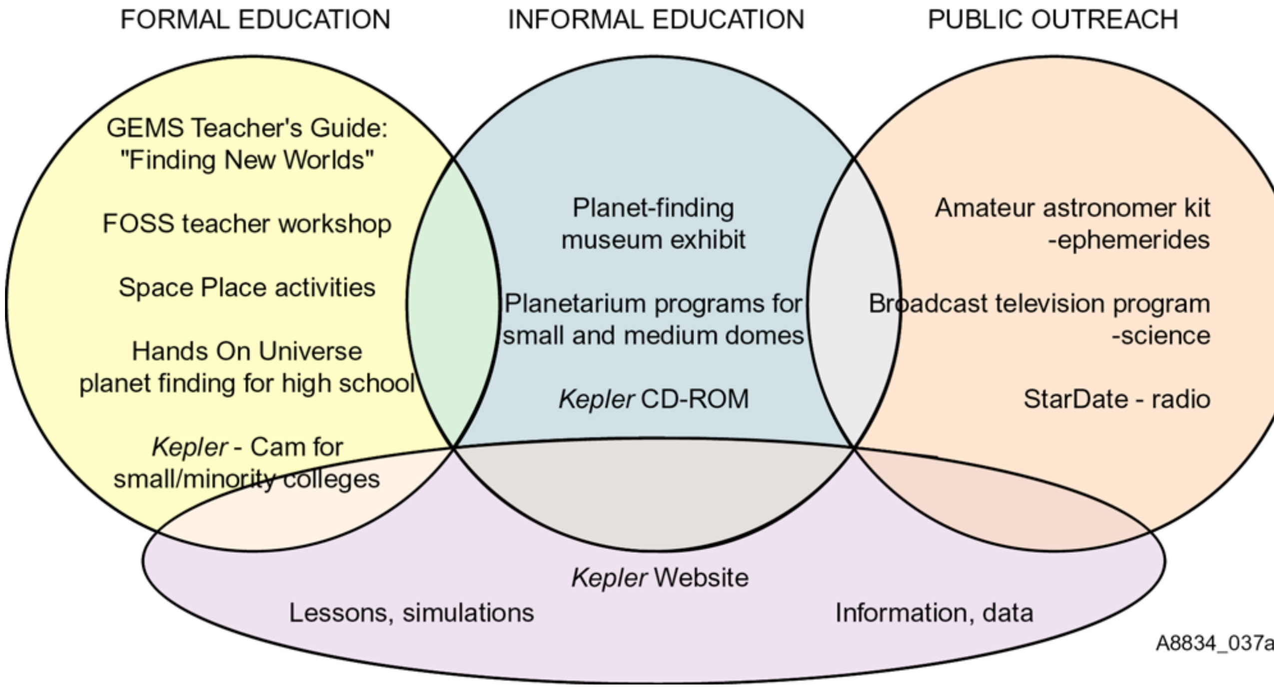
Cmd/data

DSN



Scientific Publications and Journals

EDUCATION & PUBLIC OUTREACH



The program is led by Alan Gould, Director of the Lawrence Hall of Science Planetarium, Berkeley, CA,and Edna DeVore, Director of Educational Programs at the SETI Institute, Mt. View, CA. The two Co-Is have a budget of approximately $5 M.

Great Exploration in Math and Science (GEMS) produces, tests, and disseminates a standards based teacher guide for middle school through the national GEMS network of more than 50 centers and reaches about 2 million students. FOSS (Full Option Science System) is a full length kit-base course for teachers in rural districts. Planetarium shows reach about 24 M people in the US. Alan operates the website that you might have used in becoming familiar with the *Kepler* Mission.

SMALL DISADVANTAGED BUSINESS PLAN

A Search for Habitable Planets

The *Kepler* Team is committed to providing small businesses (SB), small disadvantaged businesses (SDB), women-owned small business (WOSB) and veteran-owned small business (VOSB) concerns, historically black colleges and universities (HBCU) and other minority institutions (OMI), and HUBZone business concerns with the maximum practicable opportunities to participate in acquisitions. The *Kepler* Team's goal for SBD, including WOSB, VOSB, HBCU, and OMI, subcontracting is 8% of the total mission cost excluding the booster and Deep Space Network costs.

2. TIMELINES & OVERVIEW OF THE *KEPLER* MISSION

- Timelines
- Science Objectives
  - Implications of results
- Instrument
- Spacecraft, booster, orbit
- Organizations & responsibilities
  - Flight, Operations, Science, Management, Archiving, Navigation, Communications

EARLY TIMELINE

A Search for Habitable Planets

1971: Rosenblatt publishes first paper on transit detection of extrasolar planets
1984: Borucki and Summers publish paper on methods needed to detect transits of extrasolar planets
- Ames sponsors the first workshop on high precision photometry

1985: Borucki, Scargle, & Hudson publish paper on the detectability of transits of Earth-sized extrasolar planets
1987: Second workshop on high precision photometry sponsored by Ames & NBS (NIST)
- Operation of a robotic telescope to determine precision from ground based observations
- Test of CCD photometry at Lick Observatory
- Tests of silicon diodes, collaboration with NIST
- Mission exploration funded by HQ

1992: Discovery Program starts & requests concepts for funding
- FRESIP (Frequency of Earth-size Inner Planets) proposed to Discovery Program
- Great science but rejected because no suitable detectors believed to exist → No funding

1993: Ames sponsors a workshop to explore the astrophysics that could be accomplished by FRESIP
1994: Announcement of Opportunity (AO) for first Discovery Class Mission
- FRESIP proposes photometer in Lagrange orbit, CCD detectors,
- Rejected as too costly based on HST costs

1995: Ames/Lick group publishes a paper showing lab measurements of CCDs that have the required precision
1996: Second AO for Discovery Class Missions
- Carl Sagan, Jill Tarter, & Dave Koch advocate changing name from FRESIP to Kepler
- Mission cost estimated 3 ways, solar orbit, CCD detectors proved & results published
- Rejected because automated photometry of thousands of stars not proven

1997: Ames team builds an observatory at Lick & demonstrated automated photometry of thousands of stars
1998: Third AO for Discovery Class Missions
- Rev panel accepted science, detector capability, and automated photometry
- Rejected because ability to handle on-orbit noise not demonstrated
- HQ funds a lab testbed to demonstrate the ability to handle on-orbit noise

1999: Kepler testbed designed, built, & operational. It demonstrates the ability to handle on orbit noise.
2000: Fourth AO for Discovery Class Missions
- *Kepler* selected as one of three candidates

2001: *Kepler* accepted as Discovery Mission #10 to launch in 2006

KEPLER MISSION TIMELINE

Kepler
A Search for Habitable Planets

- 2000-Dec: Kepler selected as one of three mission concepts
  - Write Concept Study Report (CSR)
  - CSR review, Site visit review at BATC, AA presentation
- 2001-Dec: Kepler selected as Discovery Mission #10
  - Funding limitations force 1-year launch delay
  - Procurement of long-lead items begins & team is maintained
- 2002-Sept: JPL added to strengthen mission management
- 2003: Passed Systems Requirements Review
- 2004-Oct: Passed Preliminary Design Review
  - Dec. Conditional pass of Confirmation Review.
- 2005: Cost over-runs on other missions require a $35M decrease in FY'05 funding for Kepler.
  - Launch delayed until 2007
- 2006: Trade studies conducted to reduce complexity and cost of mission.
  - Articulated antenna removed at small cost to science product
  - JPL and Ames project managers replaced.
  - Critical Design Review passed
  - Replan accepted by HQ. Launch date set for Nov 2008.

CRITICAL QUESTIONS:

A Search for Habitable Planets

- Are terrestrial planets common or rare?
- How often are they in the habitable zone?
- What are their sizes & distances?
- What is their dependence on stellar properties?

SCIENTIFIC OBJECTIVES

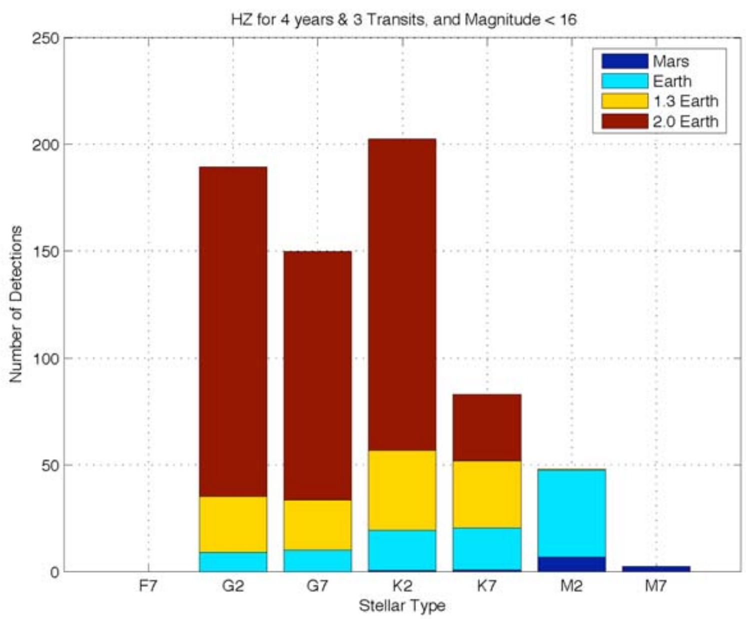
Kepler
A Search for Habitable Planets

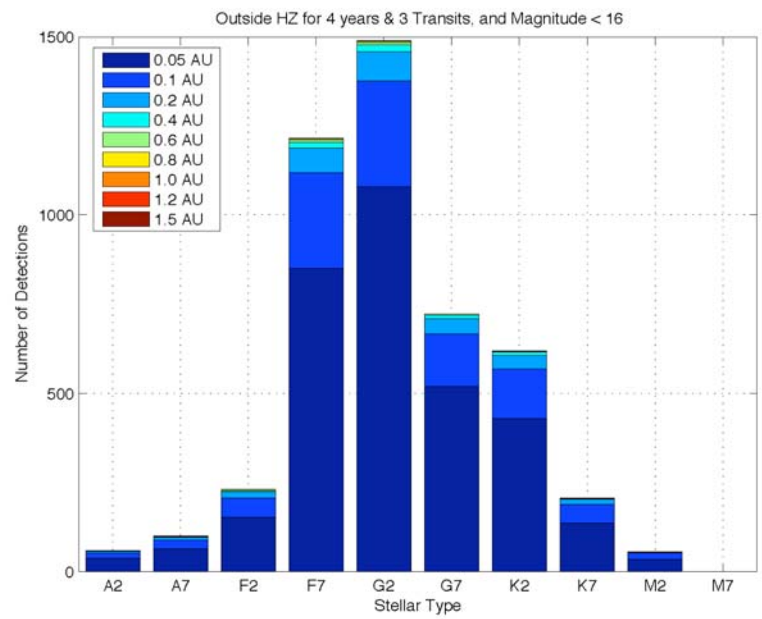
Explore the diversity of extrasolar planetary systems & determine the:

- **Frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of stellar spectral types**
- **Distribution of sizes and semi-major axes of planets**
- **If there are additional members of each planetary system using other techniques**
- **Distributions of semi-major axis, albedo, size, and density of short-period giant planets**
- **Percentage and orbital distribution of planets orbiting multiple star systems**
- **Association of discovery results with stellar characteristics**

KEPLER SHOULD DETECT THOUSANDS OF TERRESTRIALPLANETS

A Search for Habitable Planets





•Several hundred terrestrial planets are expected in the HZ if they are common. A null result would mean Earths in the HZ are rare in our galaxy.

•Several thousand Earth-size planets should be detected outside the HZ. The actual occurrence frequency will dramatically affect theories of planet formation.

VALIDATION OF DISCOVERIES

- SNR > 7 to rule out statistical fluctuations

- Three or more transits to confirm orbital characteristics

- Light curve depth, shape, and duration

- Image subtraction to identify signals from background stars

- Radial velocity
  - Medium resolution to rule out stellar companions
  - High resolution to measure mass of giant planets

- High spatial resolution to identify extremely close bkgd stars

- Color change during transit?

HARPS PLANET SEARCH PROGRAM

- Geneva Observatory
- Physikalisches Institut, Bern
- Haute-Provence Observatory
- Service d'Aeronomie, Paris
- ESO → **1 m/s**

INSTRUMENT

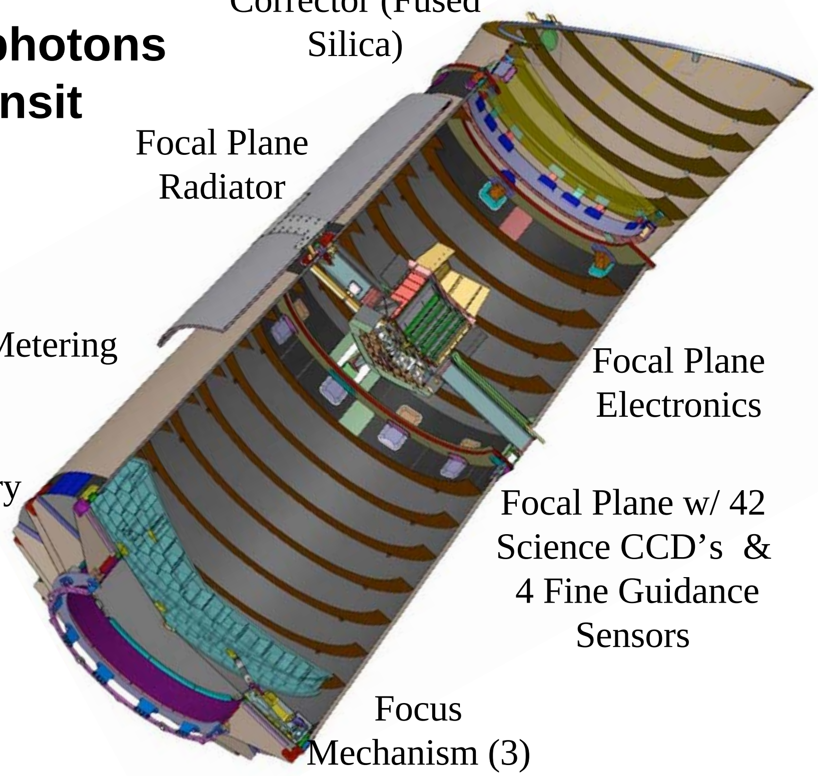
KEPLER: **A Wide FOV Photometer that Monitors 100,000 Stars for 4 years with Enough Precision to Find Earth-size Planets in the HZ**

Use transit photometry to detect Earth-size planets

- **0.95 meter aperture provides enough photons**
- **Observe for several years to detect transit patterns**
- **Monitor a single FOV continuously to avoid missing transits**
- **Use heliocentric orbit**

Get statistically valid results by monitoring 100,000 stars

- **Wide FOV telescope**
- **Large array of CCD detectors**



SPACECRAFT ENCLOSES INSTRUMENT

Kepler
A Search for Habitable Planets

Single science instrument:

Photometer: 0.95m aperture, 42 CCDs, 420-890nm, passive cooling, focusable primary

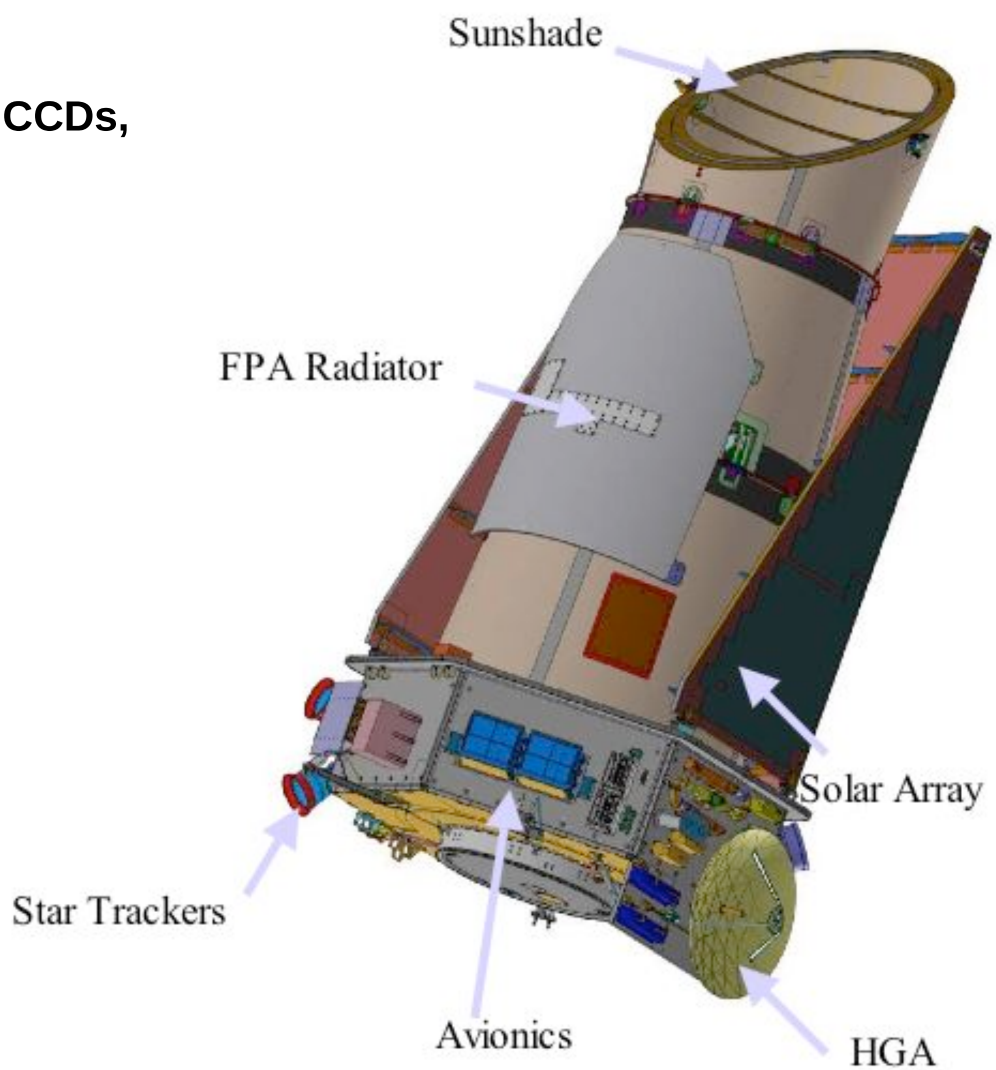
FOV: 100 sq deg. centered & fixed at 19h23m, 44º 30’

Spacecraft provides power, guidance, telecommunications, and fault protection.

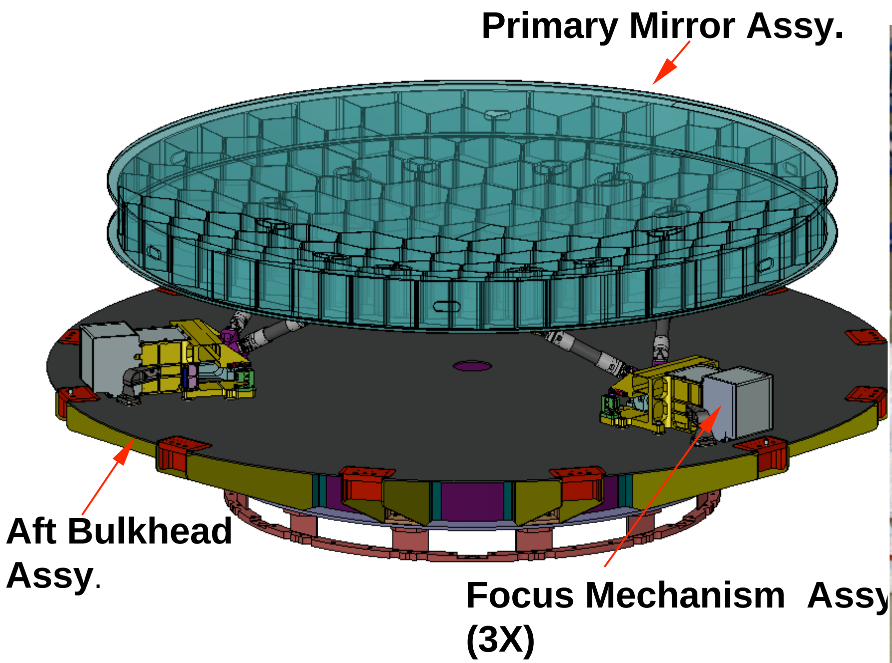
Launch Vehicle: Delta 2925-10L

Launch date: November 2008

Operational life: 4 years with expendables for 6 years



1.4 M Primary Mirror Fabrication And Bonding Is Complete



Primary Mirror Assembly passed the Environmental Test Program in August.

Assembly has been sent to JDSU for final coating.

INSPECTION OF THE 95 CM SCHMIDT CORRECTOR

Kepler
A Search for Habitable Planets

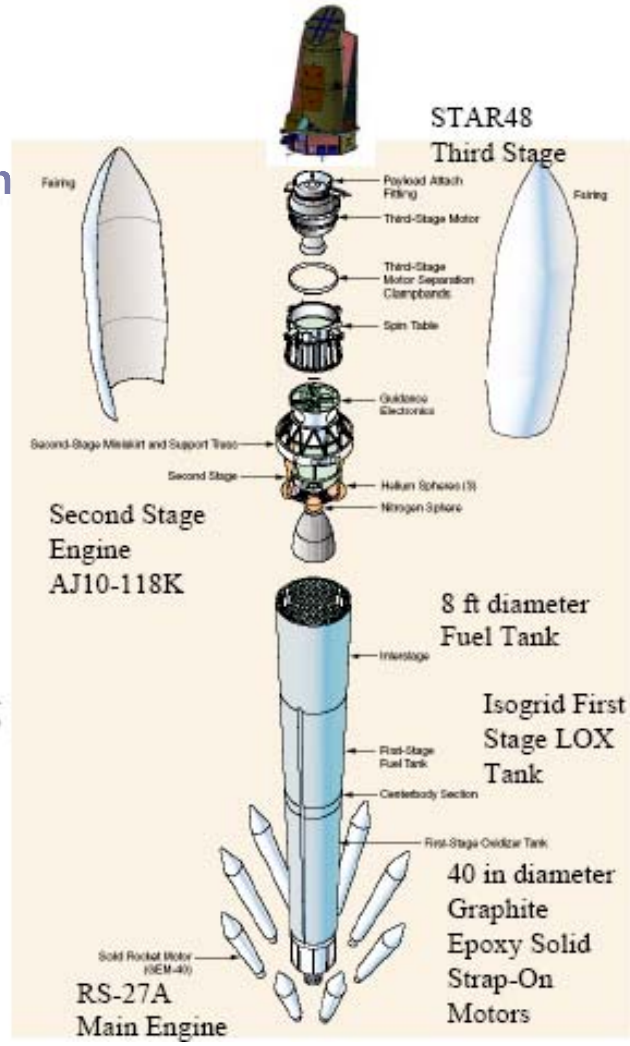
LAUNCH VEHICLE

Kepler
A Search for Habitable Planets

Launch Vehicle:	Delta II 2925- 10L
Fairing:	10 ft diameter, **30 ft length**
Fairing Access Doors:	**3 standard**
Payload Attach Fitting:	3712A
Electrical Connectors:	2-37 pin std
3rd Stage with NCS:	

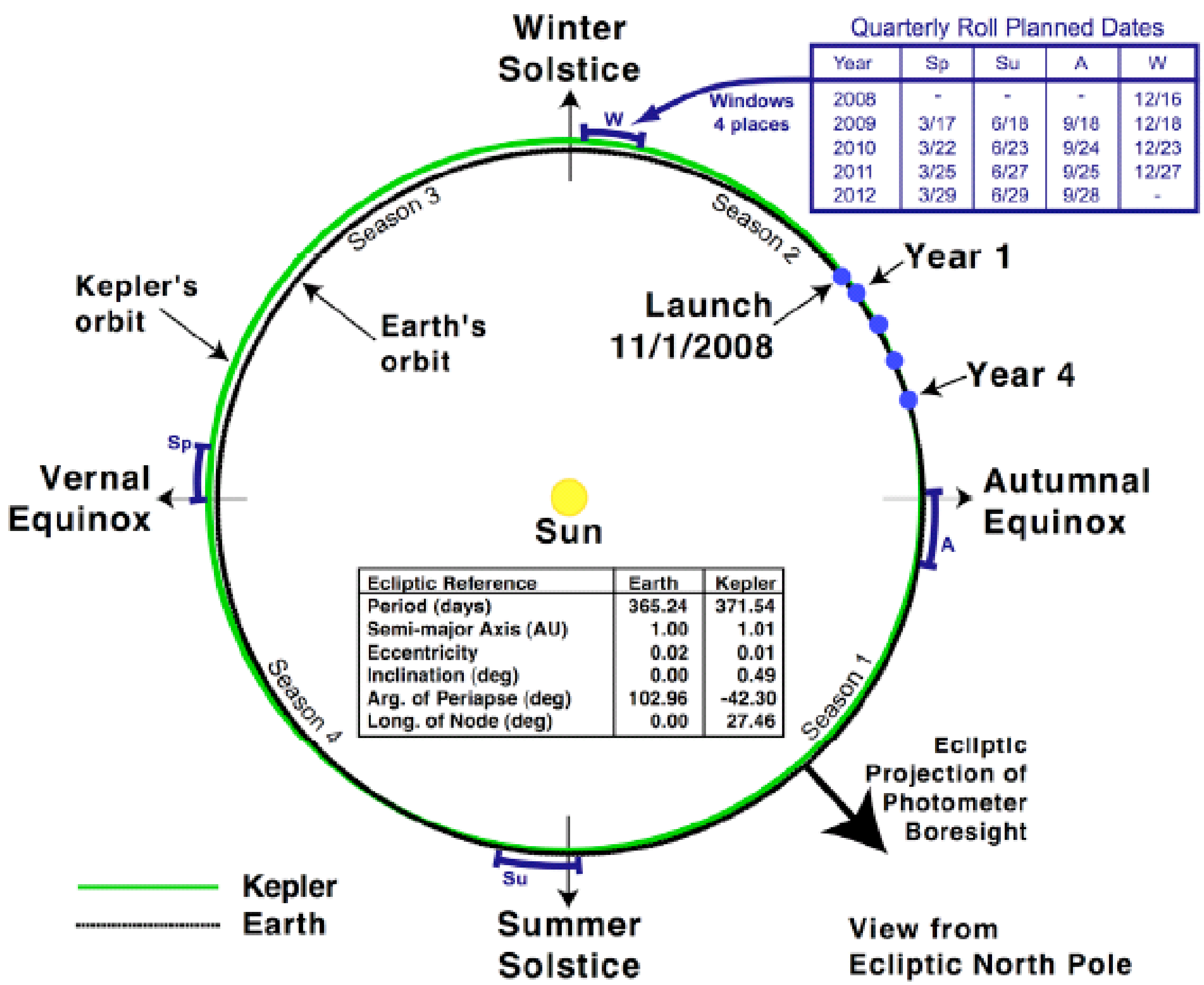
Mission Information:

Launch Date:	**Nov 2008**
Injection Orbit:	Heliocentric, earth trailing
Launch Energy:	C3= 0.6 km2/s2



KEPLER IS IN AN EARTH-TRAILING ORBIT

Kepler
A Search for Habitable Planets



Quarterly Roll Planned Dates

Year	Sp	Su	A	W
2008	-	-	-	12/16
2009	3/17	6/18	9/18	12/18
2010	3/22	6/23	9/24	12/23
2011	3/25	6/27	9/25	12/27
2012	3/29	6/29	9/28	-

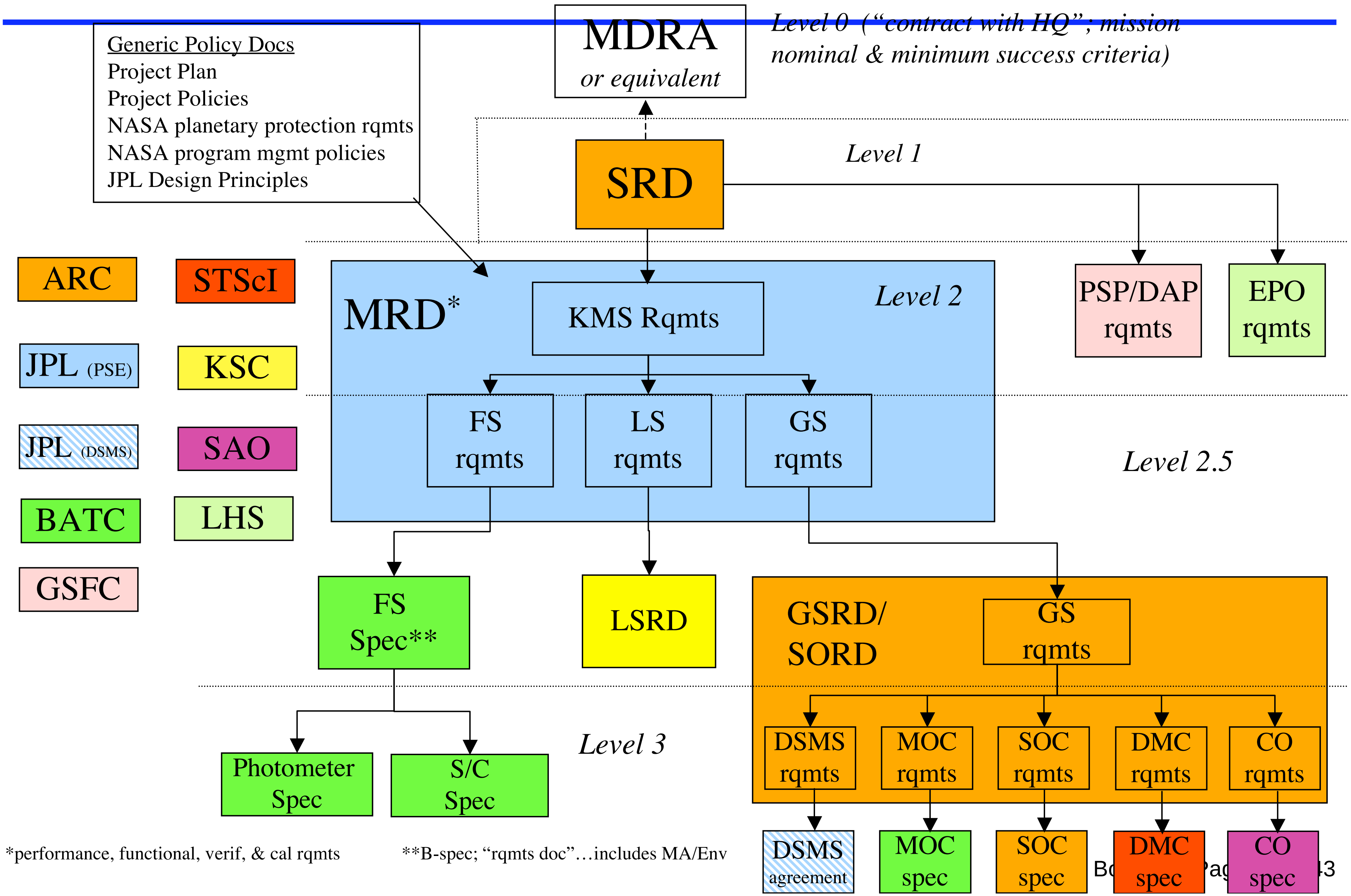
Ecliptic Reference	Earth	Kepler
Period (days)	365.24	371.54
Semi-major Axis (AU)	1.00	1.01
Eccentricity	0.02	0.01
Inclination (deg)	0.00	0.49
Arg. of Periapse (deg)	102.96	-42.30
Long. of Node (deg)	0.00	27.46

3. MISSION DEVELOPMENT

Kepler
A Search for Habitable Planets

- Phases A/B/C/D/E
- Phase A; define all requirements; Requirements Review
  - Site visit and surprise questions (telecom req.)
- Phase B; preliminary design; Prel. Design Rev.
  - Requirements flowdown; SRD, MRD,
  - Organization chart & list of documents
  - Mass, power, volume, science capability
- Phase C; Construction; Critical Design Rev.
- Phase D; Assembly, Test, Launch, Operations, & Commissioning
- Phase E; On-orbit science data acquisition

Requirements Documentation



*performance, functional, verif, & cal rqmts

**B-spec; "rqmts doc"…includes MA/Env

Baseline Design; Driving Requirements

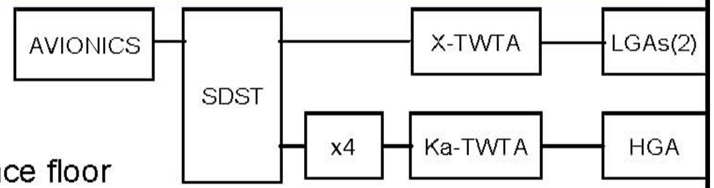
Kepler
A Search for Habitable Planets

1. Combined Differential Photometric Precision (CDPP): 20 ppm*
   - 17.35 ppm Raw Photometric Precision (RPP) = instrument & shot-noise
   - 10 ppm Stellar-variability
2. Mission Life (after 30 day Commissioning): 4 years
3. # of targets: 170,000 stars year 1 (103,000 years 2-4)**
4. Minimize false alarms (statistical and astrophysical)
5. Produce a statistically significant null result
6. Data Completeness: 91% over 4 years
7. Data Contiguity: <= 56 breaks (> 2 hour gap) over 4 years
8. Process data to detect terrestrial planets (transit & reflected light detection)
9. Orbit: Earth-trailing heliocentric (for continuous viewing & stability)
10. Launch on 3-stage Delta II 2925-10L

*single detection SNR 4.0, 6.5 hs, m_v=12, G2V, unvignetted FOV, end-of-life
** dwarf stars, m_v = 9 - 15

EXAMPLE OF A DEVELOPMENT PROBLEM

Kepler
A Search for Habitable Planets



Issue: SDST Ka-band exciter failed on MRO

- Risks to Kepler
  - Loss of mission
    - Total Ka-band failure could prevent meeting science floor
    - Ka-band failure could propagate to rest of SDST (X-band)
  - Science Degradation
    - w/o more DSN practice tracking Ka-band, operability issues could impact completeness
  - 2 tiger-teams aggressively worked over the summer (JPL SDST, Kepler Ka-band)
  - Major thrusts
    - SDST root-cause investigation & reliability improvements
    - Ensuring fault containment
    - Trading options for X-band functional redundancy (protect minimum mission)
    - Re-assessing DSN completeness and tracking robustness
- Expected outcome
  - As a minimum, replace stressed TGA8104 & improve heat-sinking for one SDST
  - Will decide by Nov 1 whether to also modify the 2nd unit and/or proceed with additional improvements to one or more units
  - Updates to fault protection & trend analysis (together with heat sinking) mitigates the risk to X-band
  - Will get more DSN Ka-band practice tracks (carrier only) with Cassini
- Analysis indicates we can preserve minimum mission with X-LGA & additional DSN time even if both Ka-band strings fail (details in backup)

25

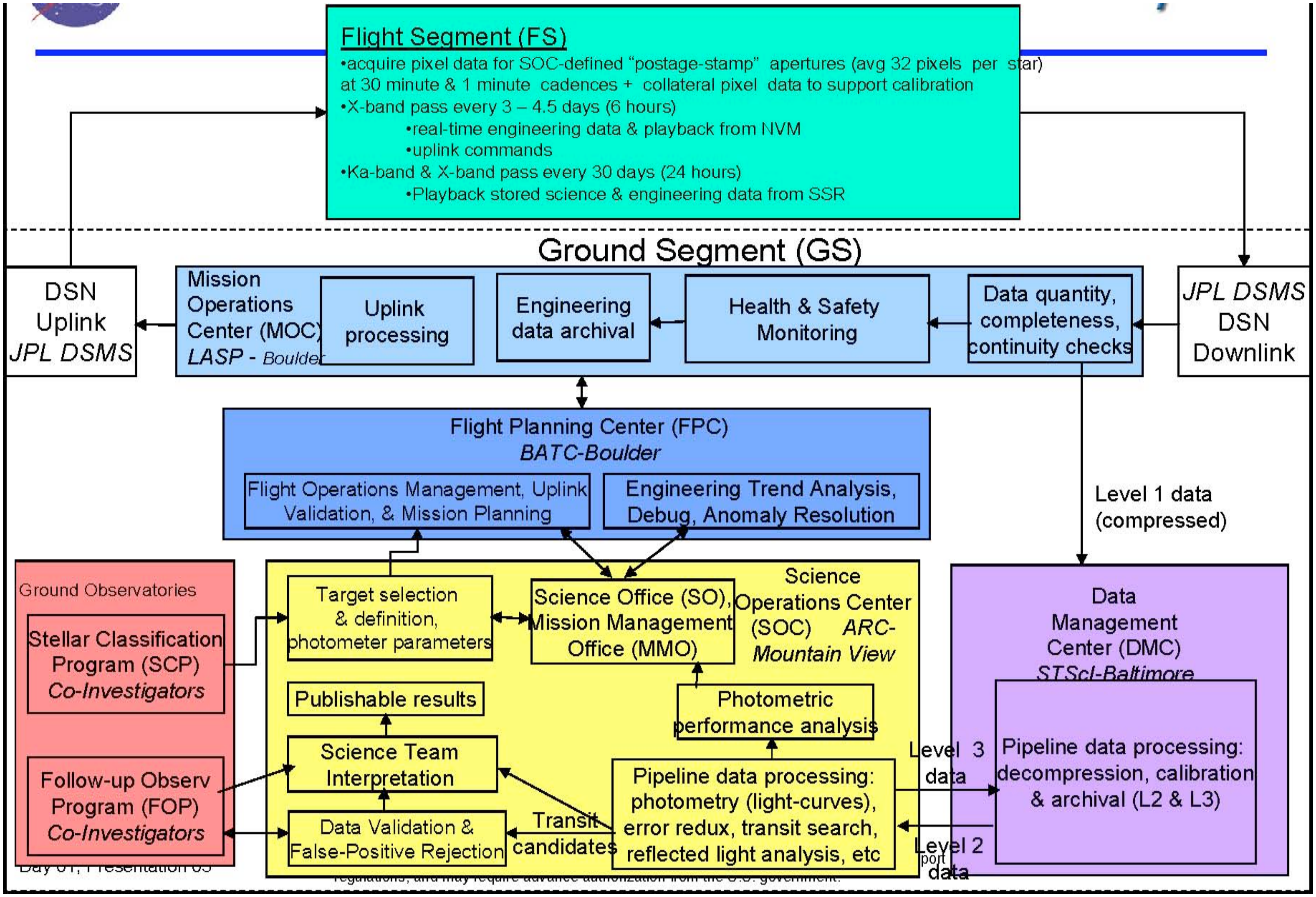
4. ANALYSIS OF THE RESULTS

A Search for Habitable Planets

- Science data flow
- Science team responsibilities & activities
- Stellar Classification Program, Follow up Observation Program, Synthesis, Publication

DATA FLOW

A Search for Habitable Planets



TASKS FOR SCIENCE TEAM

Kepler
A Search for Habitable Planets

Task	Task Description	Lead	Team Members
Characterize Planets and Planetary Systems			
1) CSR properties	Determine freq, size and semi-major axes distributions, association with stellar characteristics from data analysis. Select & downselect targets, Calculate null results.	Borucki	Koch
2) Mass of giant planets	Use highest precision RV measurements to get masses of giant planets	Latham	Cochran, Gautier, Sasselov, Marcy
3) Mass of terrestrial planets	HARPS-North observations	Sasselov	Cochran, Latham, Marcy
4) Search for moons	Search light curves for transits by moons	D. Caldwell	Jenkins, Barnes, Lissauer
5) Atmospheres	Use phase curves of reflected light to derive atmospheric properties	Sasselov	J. Caldwell, Basri (reflected light)
6) Non-transiting planets, RV	Search for non-transiting planets with high precision RV	Cochran	Latham, Marcy, Gautier, Sasselov
7) Non-transiting planets, timing		Lissauer	Sasselov, Jenkins, D. Caldwell, Jason Barnes
Characterize Parent Star of Planetary Systems and Control Stars			
1) Distance	Astrometry with Kepler data.	Monet	Dunham, Brown, Jenkins
2) Multiplicity	Search for companion stars with high SNR spectroscopy, high spatial resolution imaging, and precision multi-color photometry coupled with distance knowledge	Howell	Basri (photometry), Latham, Gautier, Marcy, Cochran
3) Size, mass, & age	asteroseismology	Gilliland	Basri (age), Brown, Dupree (hi res spectroscopy), Christensen-Dalsgaard, KASC Consortium
4) Size: best accuracy	Synthesize eff. Temp., parallax, SpT & p-mode data to get most accurate size of stars for planet size determination	Brown	Christensen-Dalsgaard, KASC Consortium

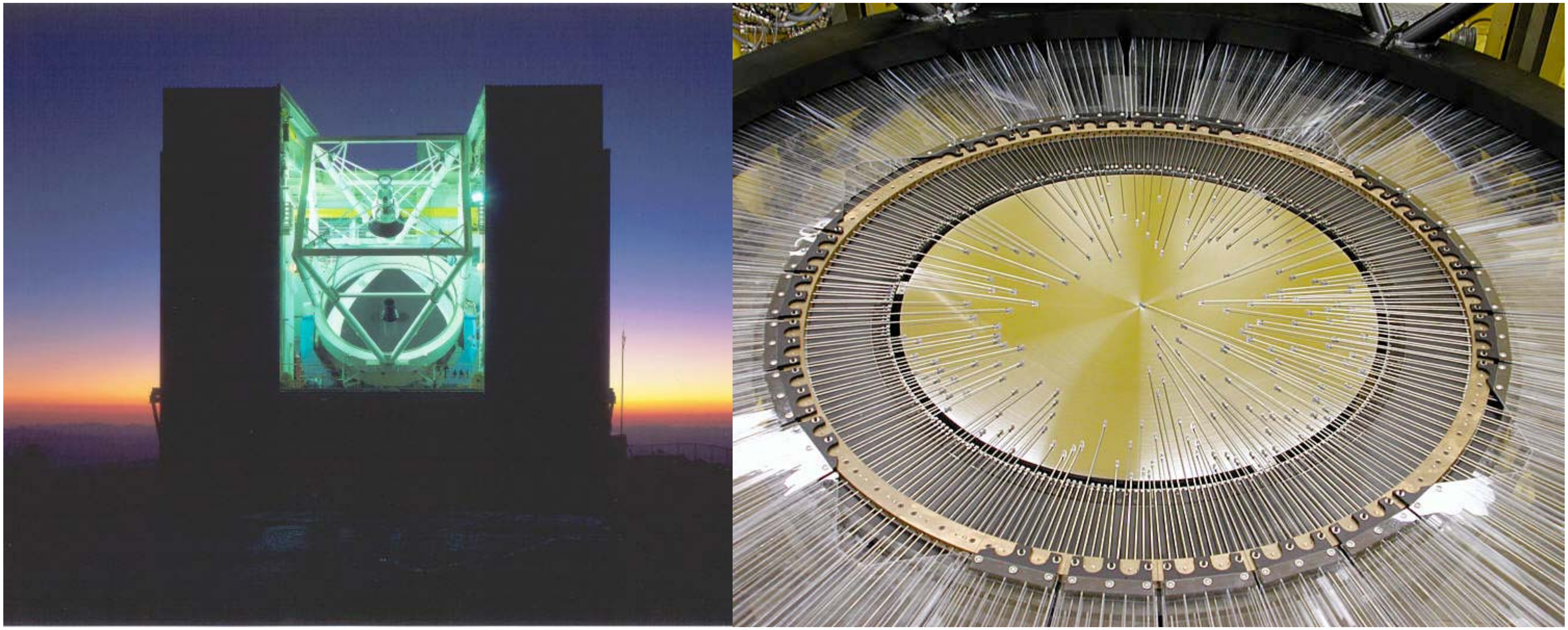
Kepler Input Catalog

A Search for Habitable Planets

- Used to select optimum targets
- Includes all known stars in Kepler FOV
  ~ 20 million stars (USNO-B)
- Photometry
  – 2MASS JHK + SDSS griz + D51
  ~ 2 million stars down to K~14.5 mag
- Astrophysical characteristics
  – Teff, log(g), [Fe/H], reddening; Mass, Radius
  – Radial and rotational velocities

MULTI-OBJECT SPECTROGRAPH TO DETERMINE THE CHARACTERISITICS OF STARS

A Search for Habitable Planets



Hectochelle on the MMT

- 240 fibers, 8 km/s resolution
- Single order: RV31 is 5150-5300A

SCIENCE COMMUNITY PARTICIPATION

Kepler
A Search for Habitable Planets

- Participating Scientist Program (PSP)
  - The PSP funds investigators whose research program is directly concerned with the detection, characterization, or understanding of extrasolar planets. Such research programs complement those developed by the PI and Co-Is.
- Guest Observer Program
  - The GOP will function similar to facilities instrument such as HST, and the data release policy of this program will be similar to that employed by such facilities. Approximately 3% of the downlink bandwidth will be available for astrophysical investigations by the GO. Observations of up to 3000 stars at the 30 minute cadence can be requested and/or 25 stars at a 1 minute cadence. Any type of object in the Kepler FOV will be observed upon request by a successful proposer.
- Astrophysics Data Program
  - This program funds investigators who wish to data mine the Kepler observations.