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Unveiling the Universe: A Comprehensive Review of the Kepler Mission's Exoplanet Discoveries

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ABSTRACT

NASA's 2009 launch of the Kepler Mission has fundamentally changed our knowledge of exoplanetary systems by revealing hundreds of planets outside of our solar system and offering previously unheard-of information into their features and frequency. It is specifically made to survey our part of the Milky Way galaxy in order to find hundreds of planets the size of Earth or smaller in the habitable zone or close to it, as well as to calculate the percentage of our galaxy's hundreds of billions of stars that may potentially host planets of this kind. It is specifically made to survey our part of the Milky Way galaxy in order to find hundreds of planets the size of Earth or smaller in the habitable zone or close to it, as well as to calculate the percentage of our galaxy's hundreds of billions of stars that may potentially host planets of this kind.The diversity of planets and planetary systems is being investigated by the Kepler Mission. The library of findings it left behind will be adequate to calculate planet occurrence rates based on factors including size, orbital period, star type, and insolation flux. The mission is getting closer to accomplishing its objective.

Keywords: Historical backgrounds, mission phases, launch profile, spacecraft orbit, and photometer

INTRODUCTION

The primary goals of the Kepler Mission are to find Earth-sized planets in the habitable zone [1] around solar-like stars (F to K dwarfs), as well as to quantify their frequency and characterize them. Transit photometry is the preferred technique since it can determine the planet's size in relation to its star as well as its orbital period [2].The planet's mass, radius, and density are found when paired with stellar parameters and radial velocity observations. High photometric precision and continuous time series data of a big number of stars over a long period of time are necessary for transit photometry.
Despite being created specifically for the intention of detecting terrestrial planets, the Kepler data set's exceptional 23 Fellow of the NASA Postdoctoral Program; valuable for stellar astrophysics research.

More than 150 of these planets have been found since the first planetary companions surrounding normal stars were found in 1995. Giant planets can be detected in between 5% and 25% of solar-like stars [3]. These planets are typically much more massive than Jupiter and Saturn. Also, the majority have high orbital eccentricities and semi-major axes of less than one astronomical unit.

The semi-major axes' unexpectedly low values suggest that they develop at several AU before losing momentum and spiralling inward toward the accretion disk. What procedures stop the inward momentum and how many planets fall into the star are unknown. Smaller planets will, of course, be eliminated by the giant planets' inward velocity, which disperses them either into the star or out of the planetary system. Another possibility is that the stars without large planets are empty of any planets because the huge planets migrated inward and fused with the star. As a result, terrestrial planet-hosting planetary systems may be quite uncommon. On the other hand, the discovery [4] of a planet with an orbital period of 2.7 days and a mass 7.5 times that of Earth suggests that at least some terrestrial planets continue to exist.

The Kepler space telescope was created to look for exoplanets, or planets outside of our solar system, by sweeping a region of the Milky Way galaxy. Scientists have discovered over 2,800 potential exoplanets and verified over 2,600 of them as real planets using information from the Kepler and extended K2 missions. A few planets are believed to be slightly larger than Earth and rocky, similar to Earth, and they orbit in the habitable zone of their stars, where liquid water—a necessary component of life as we know it—may exist.

2013 saw Kepler given a brand-new mission known as "K2." Due to the failure of two of the spacecraft's reaction wheels, engineers devised a cunning plan to rework the mission. While K2 continued to search for planets, it did so across a wider area of the ecliptic plane than previously. Along with these new research endeavours, the mission also initiated studies of objects in our solar system, exploded stars, and far-off supermassive black holes at the center of galaxies.

NASA's Kepler space telescope has run out of fuel, which prevents it from doing any science operations. This is despite the observatory spending nine years in deep space gathering data that suggests our sky is home to billions of hidden planets—more planets than stars. NASA has made the decision to withdraw the spacecraft from Earth while it is still in a safe orbit. More than 2,600 planets from outside our solar system have been discovered by Kepler, many of which may be good candidates for life.

More than 2,600 planets have been found outside of our solar system, many of which may harbor potential life.

Historical Background

This mission bears the name Johannes Kepler in honor of one of the most influential mathematicians and astronomers in history. The German astronomer made two significant contributions to science, which are recognized in the names of the Kepler Mission and its space-based telescope: his laws of planetary motion and the idea that star distances can be calculated by utilizing Earth's orbit to compute stellar parallax [5, 6].

It wasn't until later that Johannes Kepler became an independent astronomer. At first, Tycho Brahe—a well-known astronomer in his own right—taught Kepler. Kepler used Tycho Brahe's vast data on Mars's motion after his death in 1601 to eventually determine that the planet's orbit was an ellipse.

In Astronomia Nova, a book he wrote in 1609, Kepler presented his findings and consequently the first two laws of planetary motion:

1. Kepler's First Law: Planets moves in elliptical orbits with the Sun at one focus.
2. Kepler's Second Law: A planet's radius vector sweeps out equal areas in equal times.
3. Kepler's Third Law: The squares of the periodic times are to each other as the cubes of the orbital mean distance.

Fig. 1 Johannes Kepler

All planets orbit the Sun in an ellipse rather than a perfect circle, according to Kepler's first law. Many had previously believed that they did not orbit the Earth. According to Kepler's second law, a planet will move relatively slowly when its distance from the Sun is large and relatively quickly when it is small. Generally speaking, the planet's wandering area at the far end of the ellipse will be equal to the area covered at the near end.

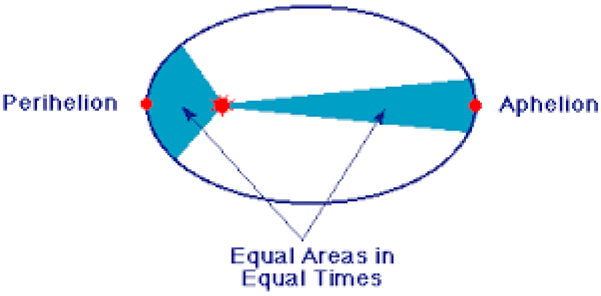

Fig. 2. Diagram of a planet in an elliptical orbit demonstrating Kepler's second law

According to Kepler's third law of planetary motion, the cube of the semi-major axis, expressed in astronomical units (AUs), equals one revolution of a planet around the Sun, also known as a period, when squared; an AU is the mean distance between the Sun and Earth. While Johannes Kepler is primarily recognized for his three laws of planetary motion, he also made several other groundbreaking discoveries in the area of astronomy. One such finding has to do with the Kepler Mission, which attempted to use the stellar parallax method to determine the distances between the stars and Earth.

This is comparable to the situation in which someone stares at a far-off object with only their left eye and then changes to gazing at the same object with only their right eye. When the angle is small, the object looks to move, but in reality, it is only subtending at a new angle.

The parallax method uses optical devices and the Earth's orbit to determine a star's distance instead of human eyes. An astronomer will once use a telescope to study a star. Six months later, the identical observation will be made, but this time the Earth will be on the other side of the Sun. Using basic trigonometry, this will show how far away the star is from Earth.

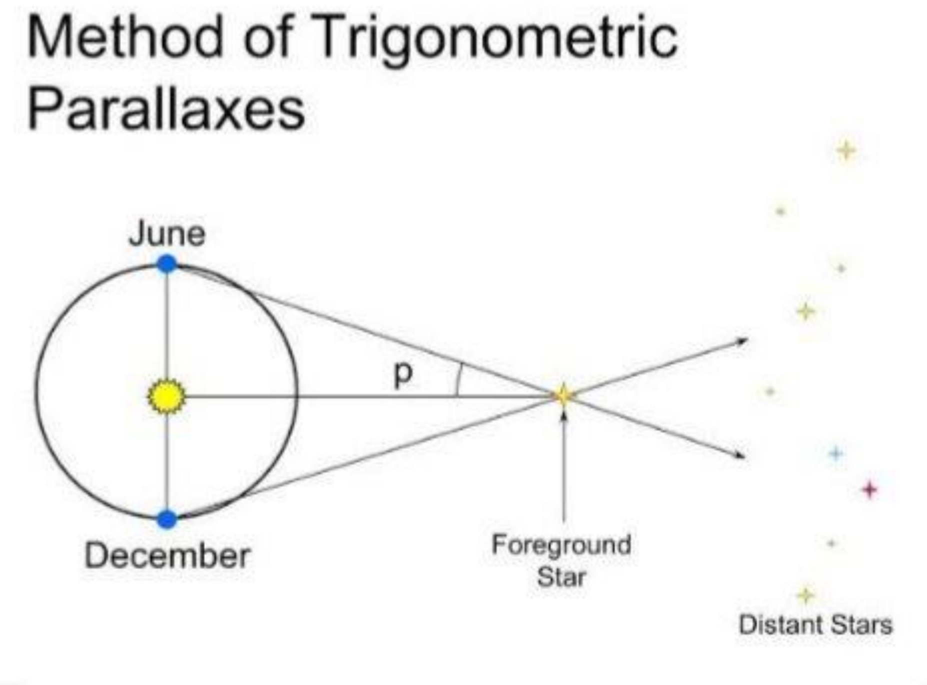

Fig. 3. A diagram of stellar parallax demonstrating the visual movement of a distant star from Earth

Mission Phases

To characterize the various activity intervals of Kepler's mission, six mission phases have been established. These include science operations, early science operations, commissioning, launch, and decommissioning.

Launch Phase

The launch phase is defined as starting three hours before launch and ending when the Kepler spacecraft separates from the rocket's third stage for planning purposes. Launch is planned from Cape Canaveral Air Force Station, Florida's Space Launch Complex 17B. The launch window for Kepler is set for March 5, 2009, until June 10, 2009. Every day, there are two three-minute launch windows.

The launch azimuths of these two possibilities are 93° and 99°, respectively, and they are separated by less than 28 minutes. For both launch windows, the launch targets are the same.

The United Launch Alliance Delta II (7925-10L) is the standard launch vehicle for Kepler. This vehicle has three stages: a bipropellant-fueled second stage, a Thiokol Star 48B solid rocket motor-powered third stage, and a first-stage liquid-fuel booster enhanced by nine solid-fuel booster engines.

During first stage flight and the early part of second stage flight, the second stage, third stage, and payload are enclosed by a stretched 10-foot (3-meter) payload fairing.

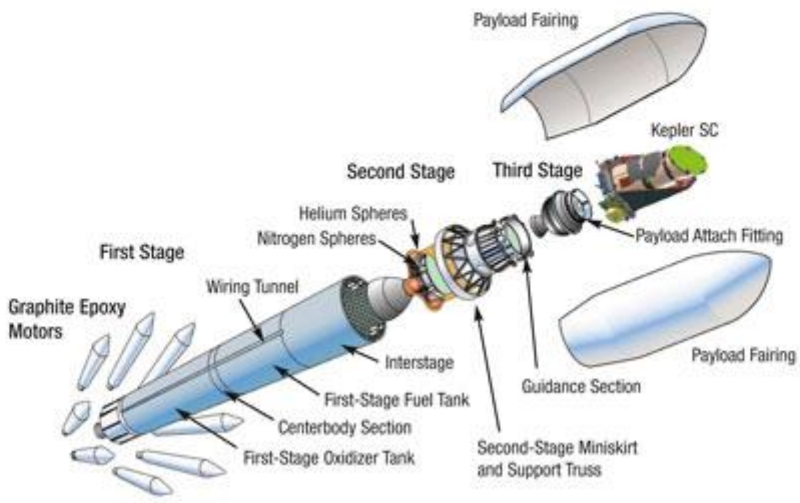

Fig. 4. Delta Launch Vehicle with Kepler Spacecraft

Kepler Launch Profile

Six of the nine strap-on solid rocket motors and the main engine of the Delta-II's first stage are fired at the moment of liftoff. After the first six solids burn out, the last three solids are ignited. When vehicle and range safety requirements are satisfied, the expended shells are subsequently discarded in sets of three. Not long after they burn out, the final set of three is discarded.

Up to the Main Engine Cutoff, the first stage engine keeps burning for approximately 4.5 minutes. After the first and second stages separate, the second stage ignites and burns for slightly over five minutes, taking around five seconds to burn. At 4.7 minutes into the flight, the payload fairing is discarded once the free molecular heating rate has decreased to a level that is acceptable. The second stage keeps burning until it reaches an altitude of 115 miles (185 kilometers) in a circular orbit around the Earth. Less than ten minutes after launch, the second stage's initial shutdown takes place.

The second stage is re-star table. The first burn of the second stage occurs during the final portion of the boost phase and is used to insert the vehicle into low Earth orbit. After parking orbit insertion, the launch vehicle and spacecraft will coast for approximately 43 minutes before reaching the proper position to begin the two-burn, Earth-departure sequence. A little more than a third of the way through the parking orbit, the launch vehicle stack exits eclipse. For the rest of its mission, Kepler will remain in the sunlight. During the coast period, the Delta II second stage will roll in a barbecue style along its longitudinal axis for thermal control of the launch vehicle to provide thermal stability.

The second stage ignites again after a coast phase, before the third stage ignites. The spin table rockets will ignite shortly after the second, second stage cutoff, propelling the third stage to a maximum rotational speed of roughly 70 revolutions per minute. After then, the second and third phases will split apart.

An ammonium perchlorate and aluminum-burning Star-48B solid rocket engine powers the spin-stabilized third stage. With an average thrust of 66,000 Newtons, the third stage solid rocket motor will burn up about 2,010 kilograms (4,431 pounds) of solid propellant in about 90 seconds. A yo-yo device will deploy and de-spin the upper stage/spacecraft stack from roughly 55 rpm to 0 rpm, give or take 2.5 minutes, following third stage burnout. Kepler will detach from the exhausted third stage motor shortly after, southeast of New Guinea, moving at a speed of roughly 1.7 meters per second (3.8 mph).

Spacecraft Orbit

In order to achieve a high detection efficiency for planetary transits, the photometer's field of view must remain outside of the ecliptic plane to prevent periodic obstruction by the sun or moon. A stellar field with a high enough star density that satisfies these viewing restrictions has been chosen close to the galactic plane.

Within the launch vehicle's capabilities, the best way to satisfy the combined sun, Earth, and moon avoidance criteria is an Earth-trailing heliocentric orbit with a period of 372.5 days. NASA's Deep Space Network provides the mission's navigation and telecommunications.

This orbit also has the benefit of having a very low disturbing torque on the spacecraft, resulting in an extremely stable pointing attitude. There are no torques from atmospheric drag, magnetic moments, or gravity gradients while one is not in Earth orbit. The torque generated by solar pressure is therefore the "largest" external torque. Although this orbit avoids the significant radiation dosage that comes with being in an Earth orbit, solar flares can occasionally occur.

Commissioning Phase

This phase starts when the Kepler spacecraft separates from the launch vehicle and should last for 60 days following launch, at which point the observatory should be fully operational. However, it could last longer if necessary. All the tasks required to get Kepler ready for its scientific mission are included in it.

During this time, the spacecraft's first signal was acquired, a valid radio contact with the ground was confirmed, and it was confirmed that the spacecraft was producing its own electricity using solar panels and that it had returned telemetry that had been recorded during launch. In this phase, the photometer's dust cover is also thrown away, the photometer is checked and calibrated, and the spacecraft's guidance system is adjusted.

Following separation, the first spacecraft signal acquisition will be aided by four Deep Space Network antennas. To obtain the one-way downlink signal from the spacecraft, two 34-meter (112-foot) antennas in Goldstone, California, and two 34-meter (112-foot) antennas in Canberra, Australia, will conduct a sweep in both frequency and angle. Ground controllers will check that all of the spacecraft's instruments and systems are functioning after they have established two-way communications with the spacecraft.

When the spacecraft can show that it can produce enough power for science operations, point and maintain attitude to a fine degree, that its X-band and Ka-band communications systems are functioning nominally, and that its photometer can collect science data from a full target set with low enough noise to allow transit detections of Earth-like planets around sun-like stars, then the commissioning phase will be deemed complete.

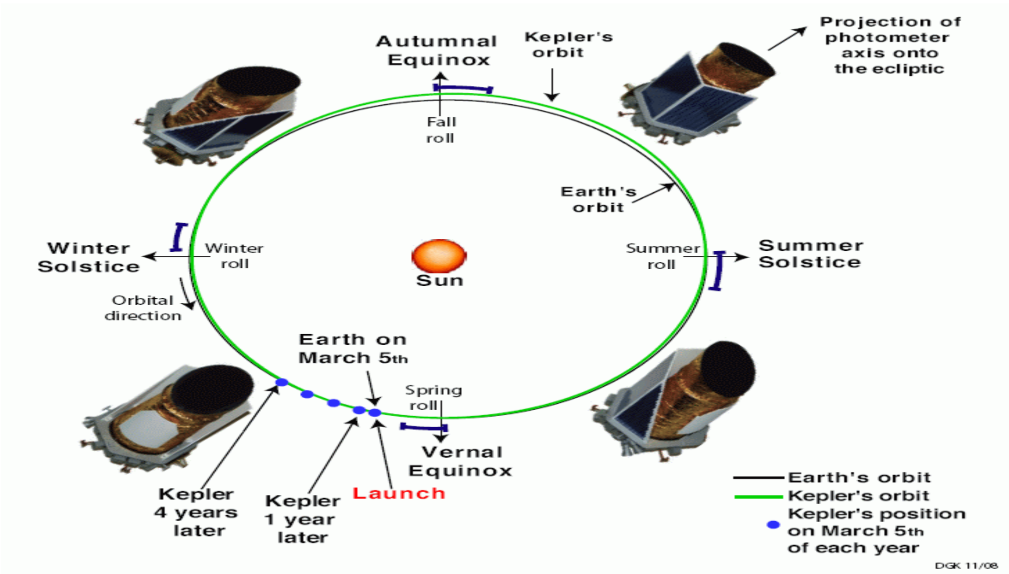

Fig. 5. Kepler Orbit (Source: Wikipedia)

Before starting the main science operations, the spacecraft and its instruments were checked and calibrated as part of the commissioning phase of the Kepler Mission to make sure everything was working as it should. This stage started as soon as the spacecraft was launched and deployed. The main steps involved are as follows:

Deployment & Initial Checkouts

Solar Panel Deployment: After launch, Kepler's solar panels were deployed to provide power to the spacecraft.
System Checkouts: Initial checkouts of all spacecraft systems to ensure they survived the launch and were functioning as expected.

Instrument Calibration

Photometer Calibration: The primary instrument, the photometer, was calibrated to ensure accurate measurement of star brightness. This involved adjusting the focus and sensitivity of the photometer to optimal settings.

Pointing Accuracy: Testing and calibrating the spacecraft's ability to accurately point at and maintain its designated field of view in the Cygnus-Lyra region of the Milky Way.

Data Acquisition & Processing Tests

Data Collection Simulation: Collecting test data to simulate actual science operations. This data was used to verify the data processing pipeline and ensure it could accurately detect changes in star brightness.

Communication and Data Downlink: Testing the communication systems used to downlink data to Earth and verify the integrity of the transmitted data.

Thermal & Power System Tests

Thermal Stability: Ensuring the spacecraft's thermal control systems could maintain the necessary temperature range for the instruments to function correctly.

Power Management: Verifying the power systems, including solar panels and batteries, to ensure they could supply continuous power to the spacecraft.

Final Preparation for Science Operations

Fine-Tuning: Any necessary adjustments based on the calibration and testing results were made to optimize the spacecraft's performance.

Readiness Verification: Final verification of the spacecraft's readiness to begin its primary mission of continuous observation and data collection.

Science & Operation Phase

The science operations phase of the Kepler Mission was the core period during which the spacecraft conducted its primary objective of discovering exoplanets by continuously monitoring the brightness of stars. Here are the key elements of this phase:

Continuous Observation

Target Field: Kepler focused on a fixed field of view in the Cygnus-Lyra region of the Milky Way, observing over 150,000 stars simultaneously.

Transit Method: The primary technique used was the transit method, where Kepler detected the slight dimming of a star's light caused by a planet passing in front of it.

Data Collection

Photometric Data: The spacecraft collected high-precision photometric data, measuring the brightness of stars with remarkable accuracy.

Quarterly Rotations: To maintain optimal sunlight exposure on its solar panels, Kepler rotated every three months. This also helped balance the spacecraft's thermal environment.

Data Transmission

Data Storage: Data was stored on board and periodically transmitted to Earth.
Communication: Regular communication sessions were scheduled to downlink the collected data to ground stations.

Data Processing & Analysis

Initial Processing: Once received on Earth, the data underwent initial processing to remove noise and other artifacts.

Light Curve Analysis: Scientists analyzed the light curves (graphs of light intensity over time) to identify potential transits indicating exoplanets.

Candidate Validation: Identified transit signals were further analyzed to confirm their planetary nature and rule out false positives.

Exoplanet Discovery & Characterization

Planet Confirmation: Through additional observations and analysis, candidate planets were confirmed, including those in the habitable zone where conditions might be right for liquid water.

Characterization: Parameters such as planet size, orbit, and distance from the host star were determined for each confirmed exoplanet.

Public Data Releases

Data Sharing: Periodic data releases allowed the global scientific community to access Kepler's findings, enabling independent verification and additional discoveries.

Community Involvement: Engaging amateur astronomers and citizen scientists through platforms like the Planet Hunters project to help analyze data**.**

Science Results

Significant Discoveries: Kepler discovered thousands of exoplanet candidates, significantly increasing our understanding of the diversity and frequency of planetary systems.

Impact on Exoplanet Science: The mission provided insights into the distribution of planet sizes and types, the architecture of planetary systems, and the potential habitability of exoplanets.

Reaction Wheel Failure and Transition Phase

Reaction Wheel Failure: In 2012 and 2013, two of the spacecraft's four reaction wheels failed, impacting its ability to maintain precise pointing.

Transition to K2: After attempts to fix the reaction wheels failed, the mission transitioned to the K2 "Second Light" phase, using the remaining functional wheels and solar radiation pressure to stabilize the spacecraft.

K2 Mission Phase

Revised Mission Objectives: The K2 mission involved observing different fields along the ecliptic plane, broadening the range of astronomical phenomena studied, including supernovae, star formation, and other exoplanets.

New Data Collection: Kepler continued to collect valuable data with its new observational strategy.

Final Data Release: Continuous release and analysis of data collected during the K2 phase.

Photometer

You might think of the photometer as a multi-channel light meter. It is not intended to produce visual representations of the sky, but rather to concurrently record minute changes in brightness in over 100,000 stars. Figure 6 depicts the photometer, a traditional Schmidt telescope.

The spectral bandpass is as broad as feasible from 420 to 865 nm (50% responsivity) in order to avoid the Ca II H&K lines, which are known to be the most changeable part of the solar spectrum. Low shot noise is required to achieve the CDPP. It is the largest Schmidt telescope in space and the ninth largest telescope ever constructed. A trade-off between aperture and field-of-view (FOV) revealed that a 0.95-meter aperture and a FOV of >100 square degrees is the most practical option in giving the highest number of useful stars [7]. The goal of having the richest star field possible while staying well out of the ecliptic plane, allowing for continuous monitoring of the field throughout the orbital year, determines the celestial FOV. The selected position is just off the galactic plane and >55° from the ecliptic plane, with RA=19h 36m and Dec=34°40'.

Optical components in the meter class are usually long-lead, high-risk devices. For these components, the critical design review (CDR) has already been finished. The 85% lightweight primary mirror has a ULE Frit bonded construction, while the Schmidt corrector is made of fused silica. These are both products of Corning Inc. At Brashear LP, optical figuring is being done. The corrector is expected to be delivered this autumn. Corning has crumpled the primary mirror. The primary mirror is expected to be delivered in the middle of 2005.

A graphite cyanate/ester structure that provides the thermal-mechanical stability between the corrector, primary mirror, and focal plane keeps the optics aligned. The only mechanisms on the photometer are the redundant one-time aperture-cover release mechanism and the mirror focus mechanics.

The photometer's base is enclosed by the spacecraft bus, which also houses the arrays and the systems for power, communication, and navigation. There are two antennas available for data downlink and uplink commanding, each with a different frequency coverage and gain pattern. Data transport to the Deep Space Network (DSN) is accomplished at high speed via a steerable high-gain antenna that operates at the Ka band. Other from the ejectable cover, it is the sole articulated part.

Every few days, when communication is established with the DSN, data at a rate of about 1 GByte per day is captured and subsequently transmitted to the ground. With the help of four tiny guiding sensors positioned on the photometer focal plane, the spacecraft is able to point quite steadily. The momentum wheels are desaturated by tiny thrusters. There are enough consumables on board to make the expedition last six years.

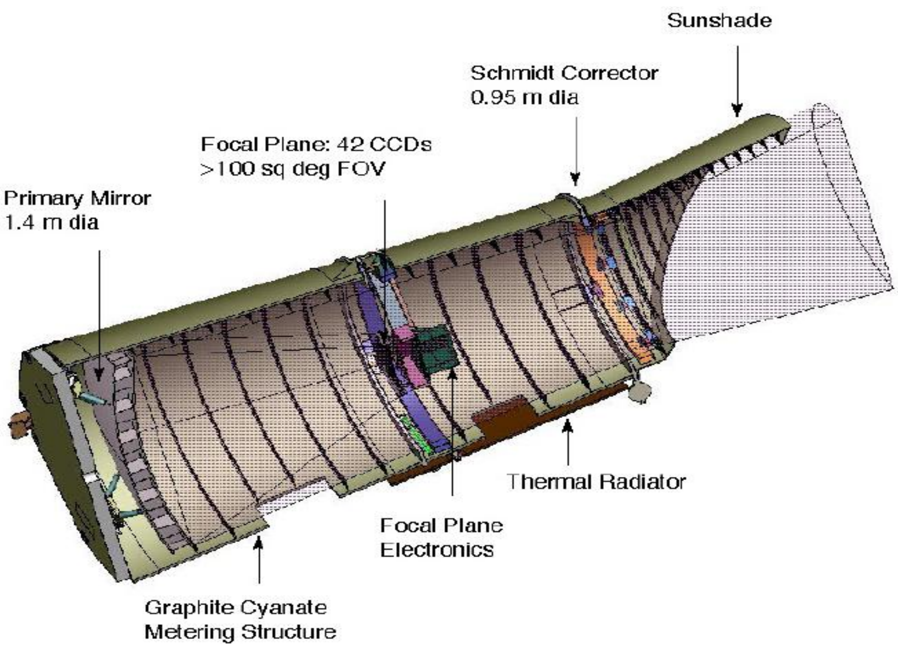

Fig. 6. The Photometer consisting of the CCDs, telescope and processing electronics [7]

Boulder, Colorado-based Ball Aerospace and Technology Corporation (BATC) is building the spacecraft and the photometer. Development of the photometer, mission and operations, and scientific analysis are overseen by NASA Ames. JPL oversees the development of spacecraft and missions. There is a longer and more in-depth explanation of the mission concept in [8, 9].

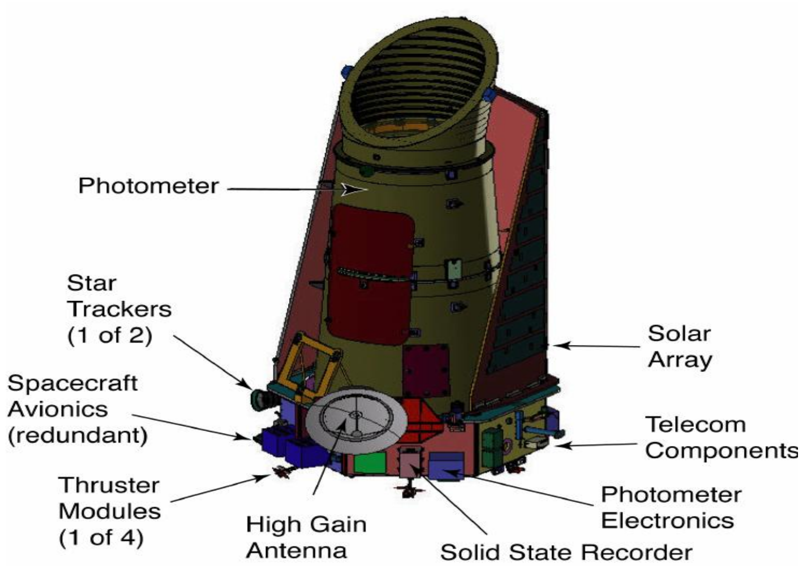

Fig. 7. Integrated Spacecraft & Photometer

Future Scope

The Kepler Mission's legacy will continue to shape exoplanetary science and exploration in several key ways:

A. **Ongoing Data Analysis**: Continued examination of Kepler's extensive data set will likely lead to the discovery of additional exoplanets and refined knowledge of known ones.

B. **Complementary Missions:** Missions like TESS and the James Webb Space Telescope (JWST) will build on Kepler's discoveries by finding new exoplanets and characterizing their atmospheres.

C. **Future Exoplanet Missions**: Upcoming missions such as PLATO and CHEOPS will expand the search for exoplanets and study their properties in greater detail.

D. **Astrobiology:** Research will focus on identifying potentially habitable planets and detecting biosignatures in exoplanetary atmospheres.

E. **Advanced Detection Techniques**: Innovations in technology and data analysis methods, including machine learning, will enhance our ability to find and study smaller, Earth-like exoplanets.

F. **Stellar and Planetary Formation**: Kepler's data will continue to inform theories about planetary formation and the impact of stellar activity on planetary environments.

G. **Public Engagement**: Citizen science projects and educational initiatives will leverage Kepler's discoveries to involve the public and inspire future generations.

CONCLUSION

The Kepler Mission has fundamentally transformed our understanding of the universe by unveiling the vast diversity and prevalence of exoplanets. Through its groundbreaking observations, Kepler discovered thousands of planets orbiting distant stars, including many Earth-sized planets in habitable zones. This mission has provided invaluable data that continues to be analyzed, yielding new discoveries and insights into planetary formation, the conditions for habitability, and the potential for life beyond our solar system.

Kepler's legacy extends beyond its immediate scientific achievements. Moreover, Kepler has engaged and inspired the global community, fostering public interest in space exploration and encouraging citizen science initiatives. Its contributions to education and public outreach have helped cultivate a new generation of scientists and enthusiasts dedicated to the quest for knowledge about our universe.

So finally, the Kepler Mission's impact on the field of exoplanetary science is profound and enduring. It has opened our eyes to the myriad worlds that exist beyond our solar system and laid a robust foundation for future explorations. As we continue to analyze Kepler's data and embark on new missions, the insights gained will undoubtedly propel us closer to answering the age-old question of whether we are alone in the universe.

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