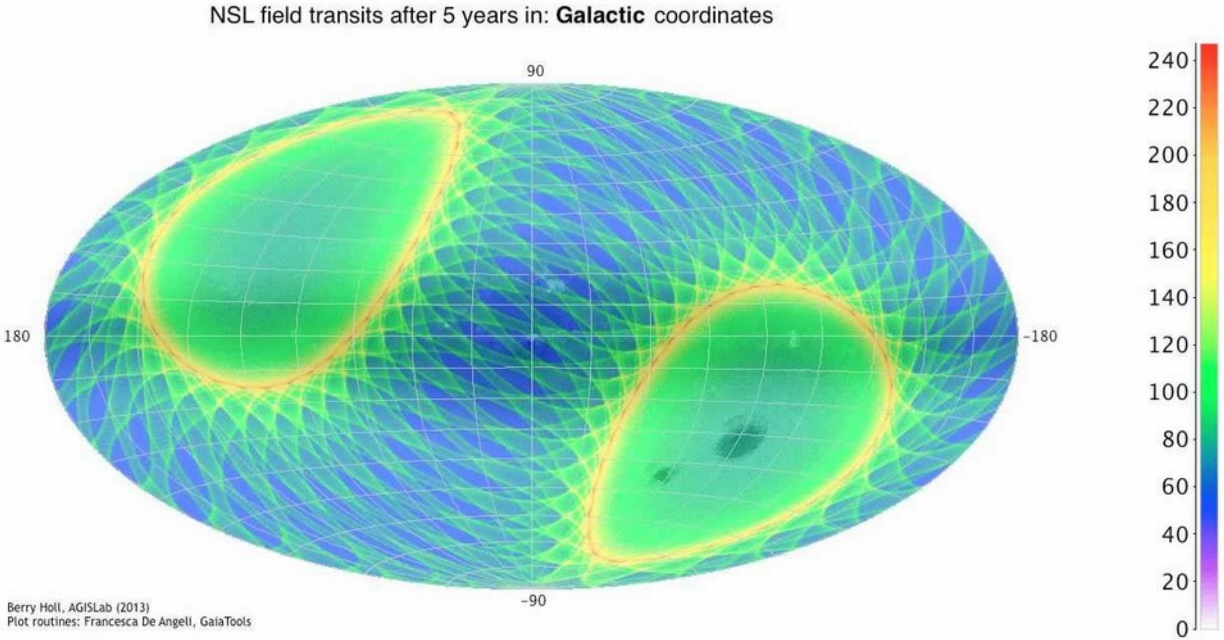
(Day 11)

Astrometry

(Soyuz carrying Gaia into orbit;
Credit: ESA - D. Ducros)

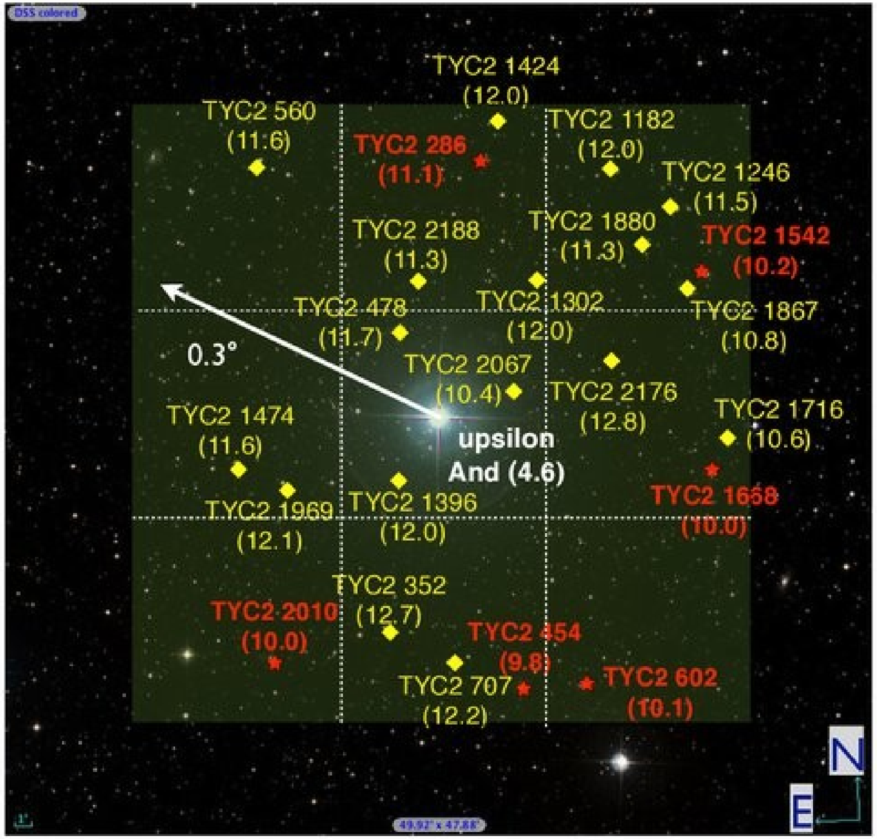
Today



1. Astrometry
2. Gaia

What is astrometry?

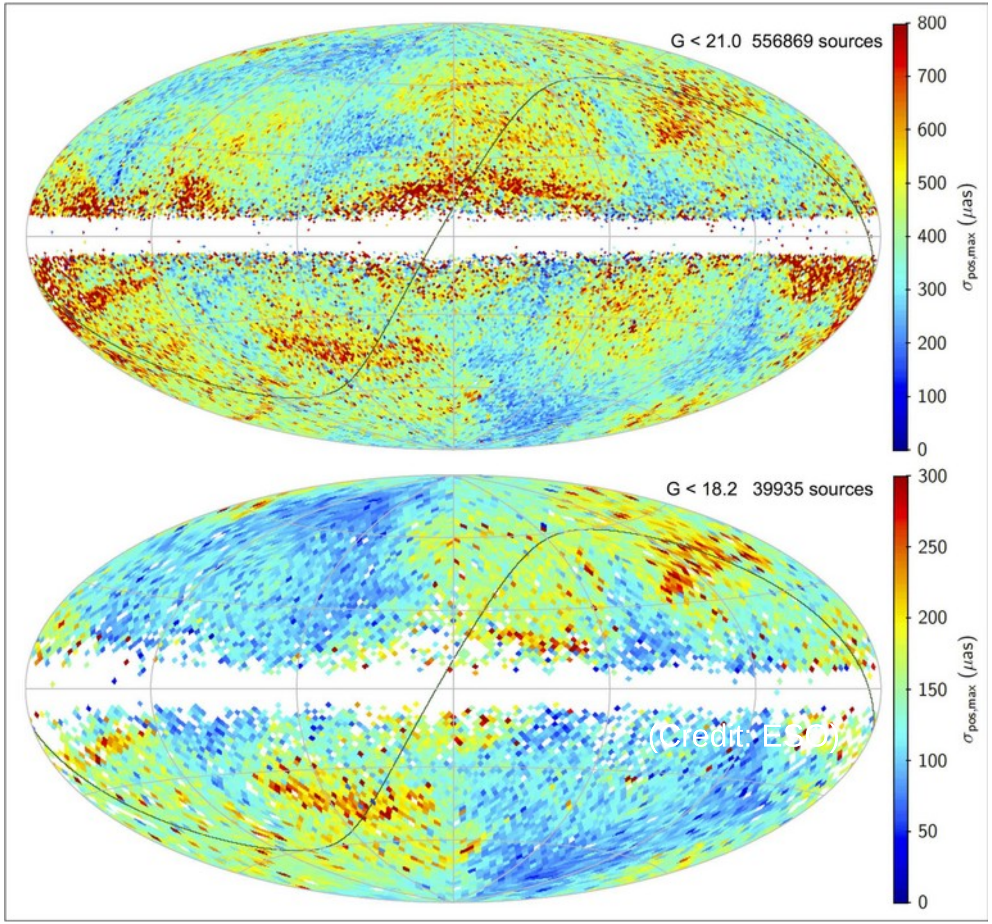
- Measuring the positions of celestial objects, and by extension the changes in time of those positions; and distributions of sources
- The oldest branch of astronomy, cataloguing the positions of objects
- e.g., measurements by Tycho Brahe were used by Kepler for his planetary laws
- When astrophysics developed, astrometry was left to the side…
- But has gradually found renewed interest (with developments like CCDs, interferometry, …)
- And finally came back to the spotlight with Hipparcos and now *Gaia*!



(Malbet et al. 2014)

Reference frame

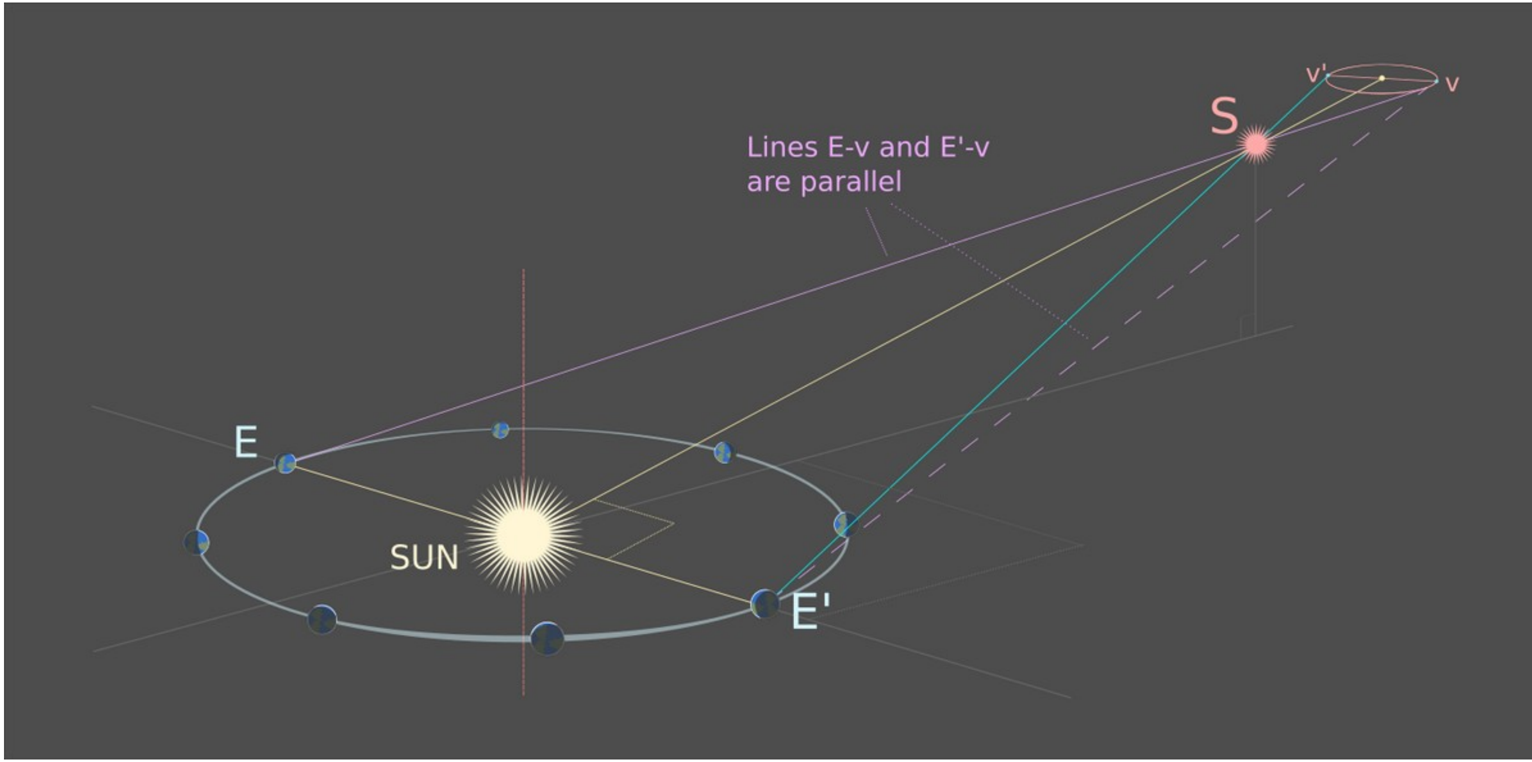
- Practical realisation of the coordinate system in space
- Standard objects to be used for determining positions of other sources
- The International Celestial Reference System (ICRS) realized on the basis of distant quasars
- Radio VLBI observations (third international celestial reference frame, ICRF3; Charlot et al. 2020)
- Gaia observations of > half a million quasars, the Gaia Celestial Reference Frame (based on optical observations)



Credits: ESA/Gaia/DPAC, François Mignard, Sergei Klioner, and the co-authors of the paper "Gaia Data Release 2: The celestial reference frame (Gaia-CRF2)"

Stellar Parallax

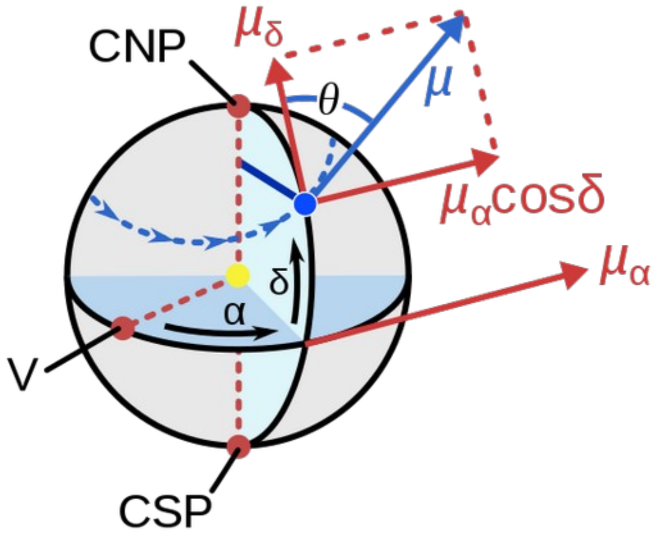
- Apparent shift in position because of Earth’s orbit around the Sun
- The angle measured in arcsec gives the distance in parsecs ($\pi = 1 / d$)
- Parallax is a primary distance indicator

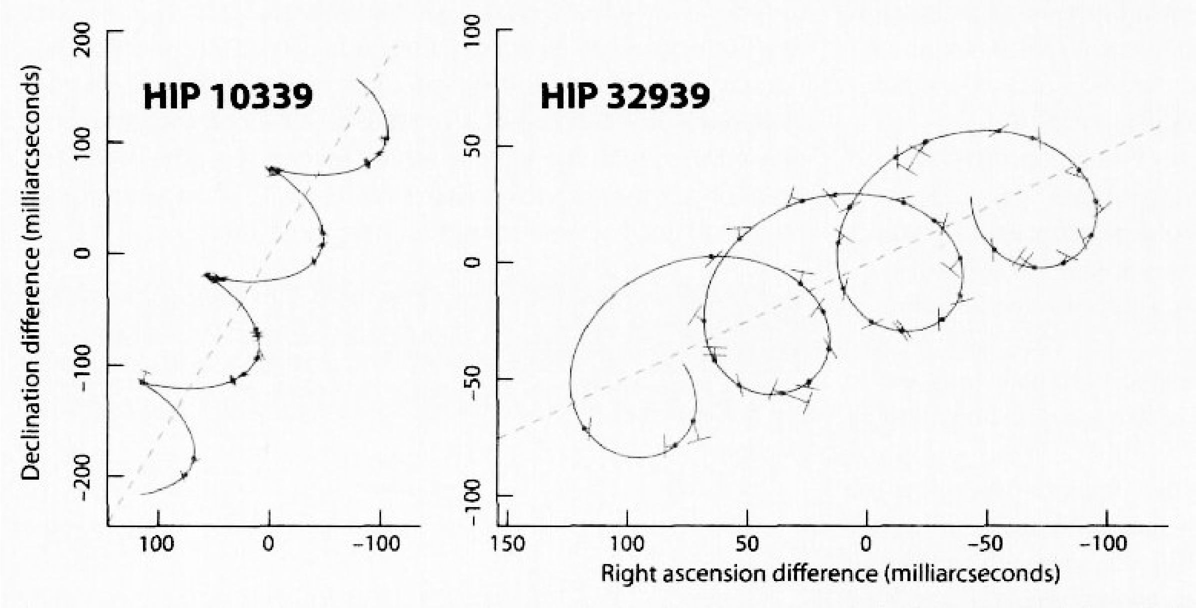


(Credit: Wikipedia; PdeQuant cc4.0)

Stellar Proper motion

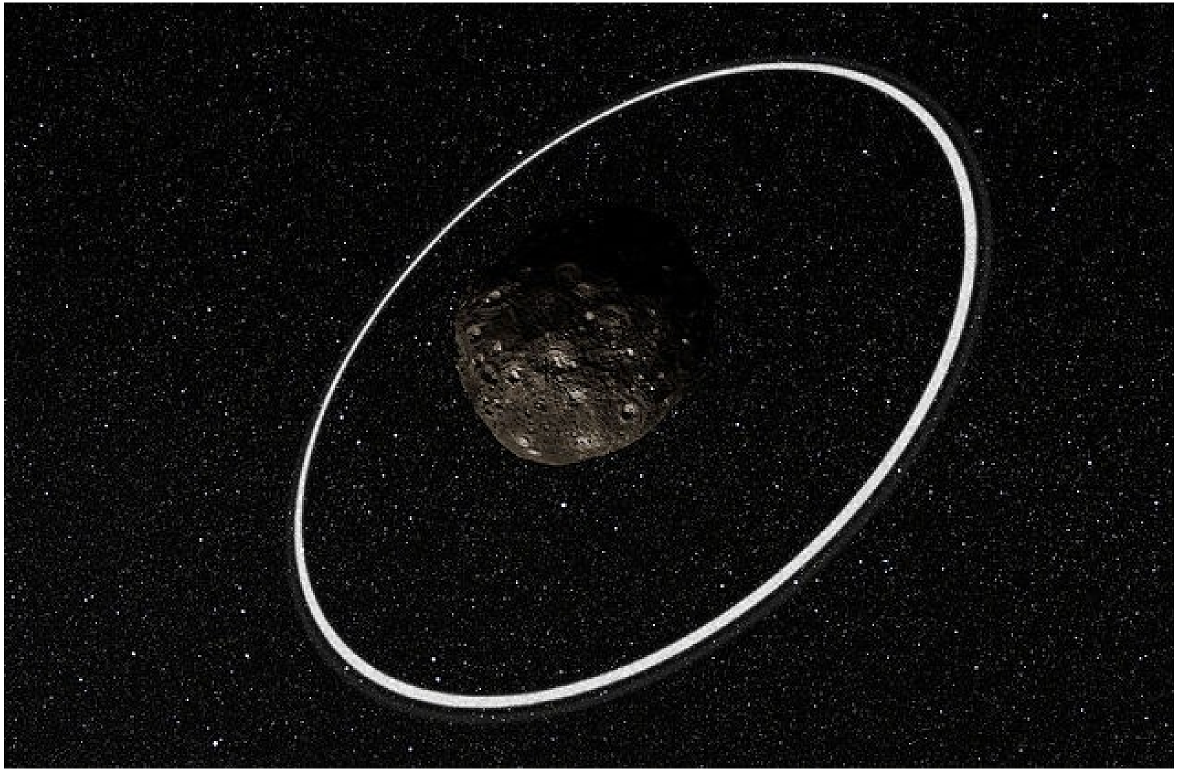
- Proper motion: projections on the sky of the star motion with respect to the solar system
- The motion is usually decomposed in the equatorial system





Solar system bodies

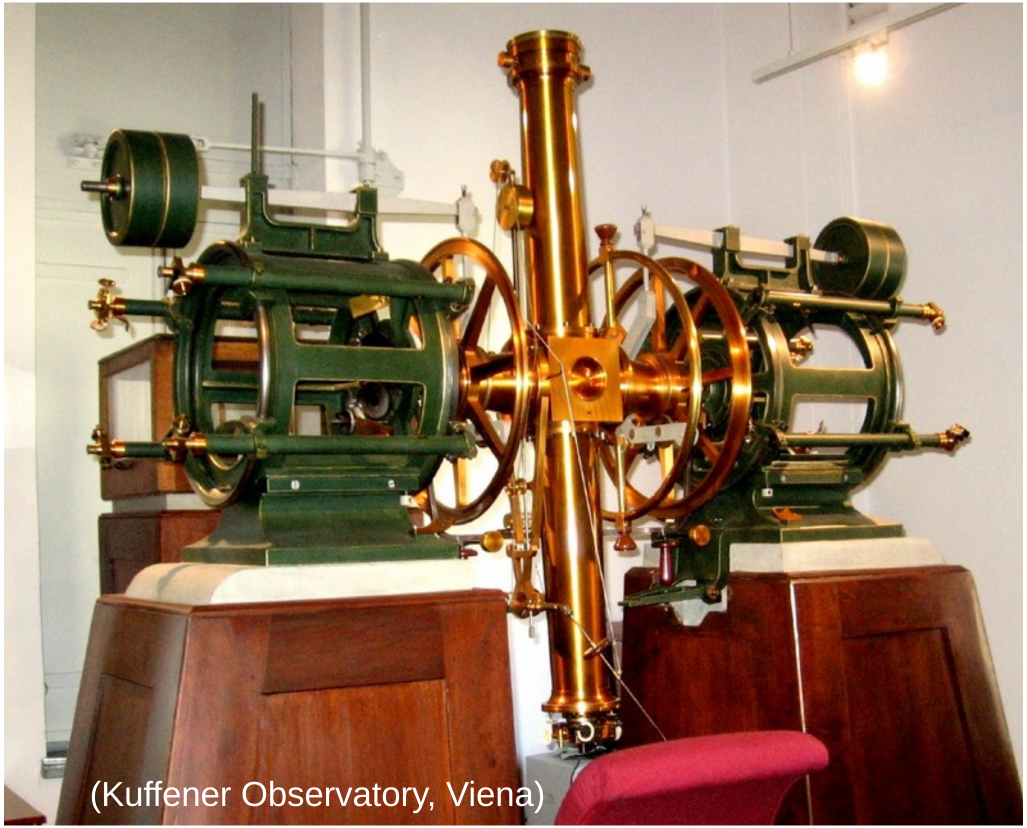
- Solar diameter (solar physics and climatology)
- Planetary motions and general relativity
- Planetary satellites (celestial mechanics and space missions)
- Stellar occultation by minor bodies (discovery of atmospheres, moons and rings)
- Search for distant solar system objects



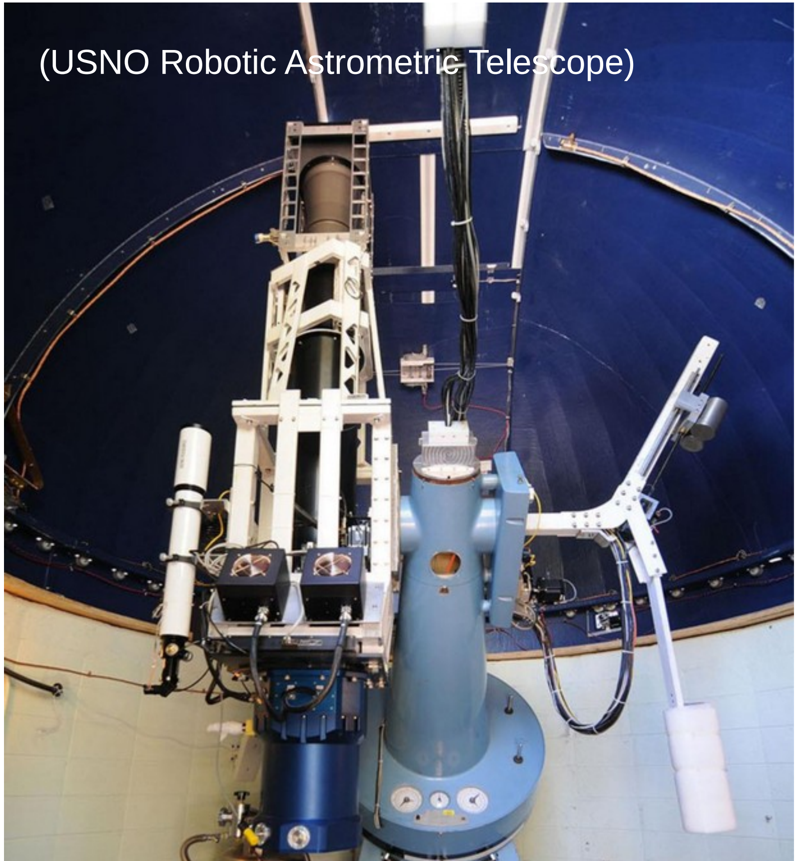
(Rings of the centaur 10199 Chariklo)

Instruments

- Meridian circle:


(Kuffener Observatory, Viena)

- Astrograph:


(USNO Robotic Astrometric Telescope)

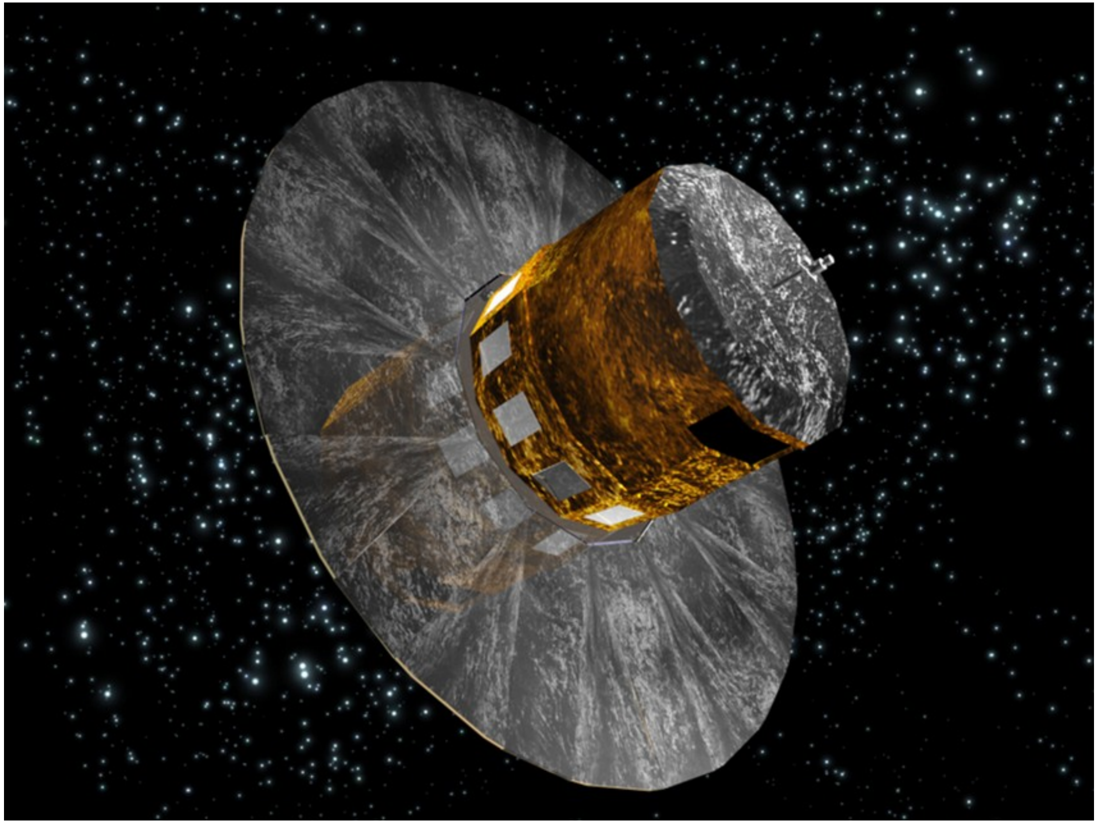
Hipparcos satellite

- First space mission to measure positions and motions of stars in the Galaxy
- Launched August 1989; end of operations in March 1993
- Hipparcos Catalogue: 118 218 stars with high precision; Tycho 2 Catalogue: 2 539 913 stars (less precise)
- “Reflective Schmidt telescope” with two apertures receiving light from two fields
- A beam combiner (two half mirrors of 29cm, glued at 29 deg) sends light to a fold mirror, then a spherical mirror, that images the two fields in a single focal plane
- A system of grids, at the focal surface, spaced by 1.208 arcsec

(Credit: ESA)

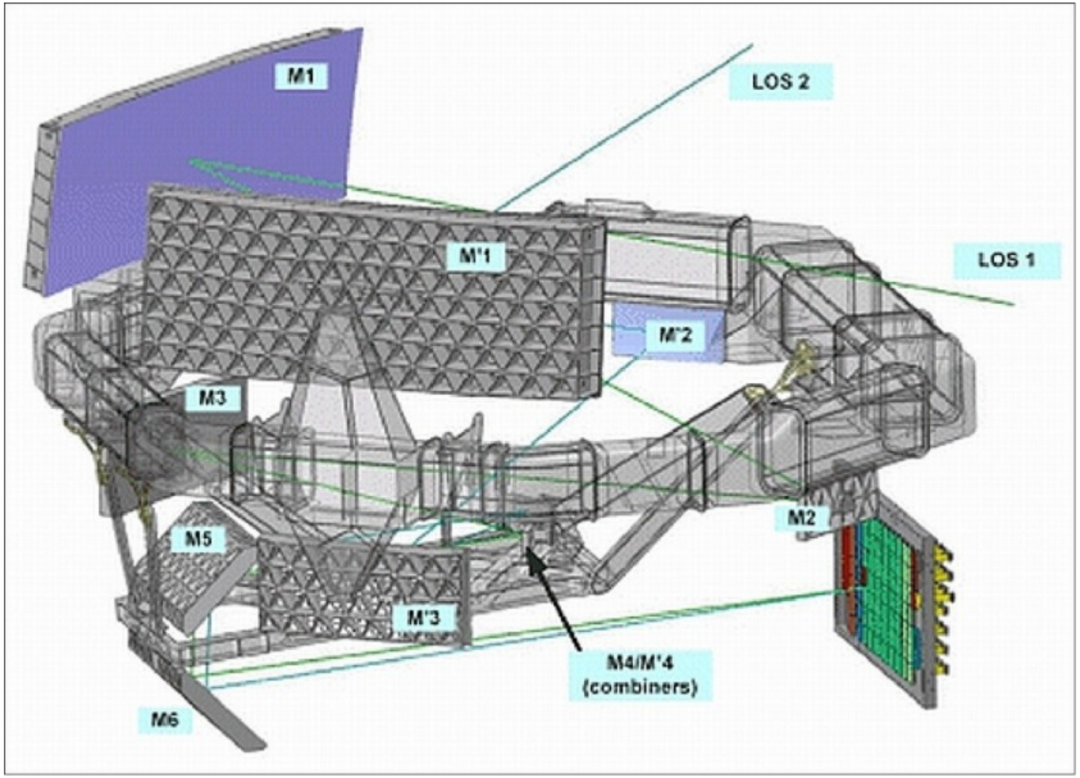
Gaia satellite

- Launched in December 2013 for a 5-years nominal mission (still in operation now)
- At the L2 Lagrange point
- Measurements for > 10^9 stars
- In the Galaxy and bright stars in nearby galaxies
- Tens of millions of variables
- Astrometric identification of unresolved binaries (on top of parallax and proper motion)
- Astrometric discovery of exoplanets
- Identification of solar system objects



Gaia telescopes

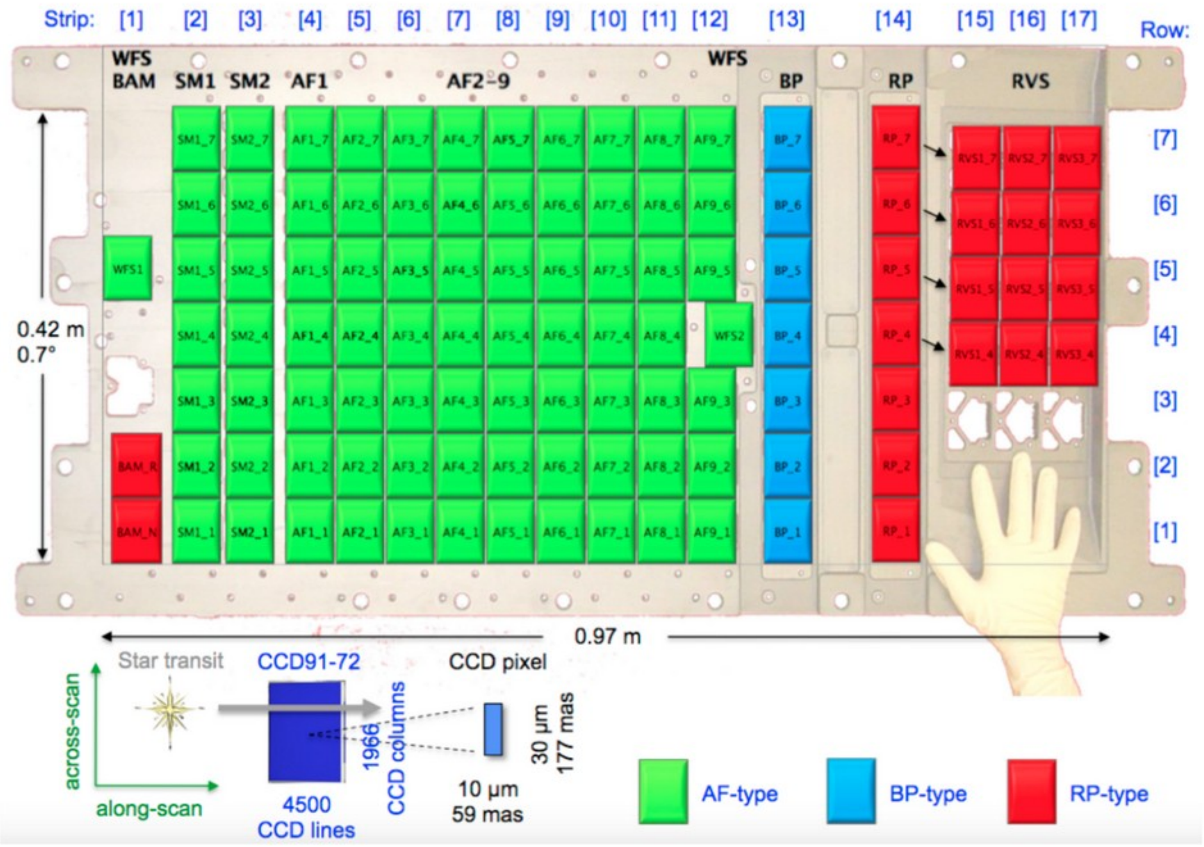
- Two three-mirror anastigmatic telescopes (1.45 m × 0.50 m)
- Pointing in directions separated by 106.5 degrees
- Two M4 mirrors (flat beam combiners)
- Two common folding mirrors M5 and M6 (silicon carbide, coated with protected silver)
- M2 has actuators for alignment and focusing
- Two wavefront sensors at the focal plane



(Credit: EADS Astrium)

Gaia focal plane

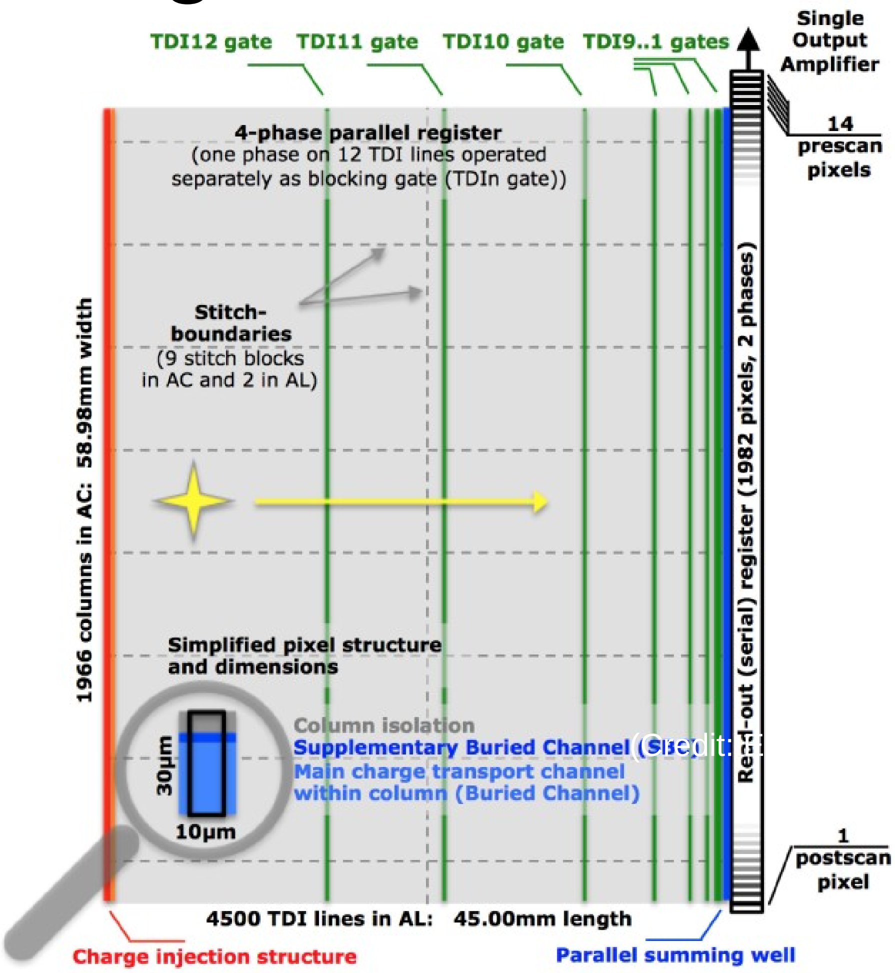
- 106 CCDs
- Back-illuminated, full-frame, 4500x1966 columns with 10x30 µm pixels
- “Broadband” and “blue” types: 16µm thick with different anti-reflection coating (650nm, 360nm)
  - Broadband: AF, SM, and WFS
  - Blue: BP
- “Red” type: 16µm thick, high-resistivity, anti-reflection coating for long wavelength (750nm)
  - RP and RVS



(Gaia collaboration 2016)

Time-delayed integration

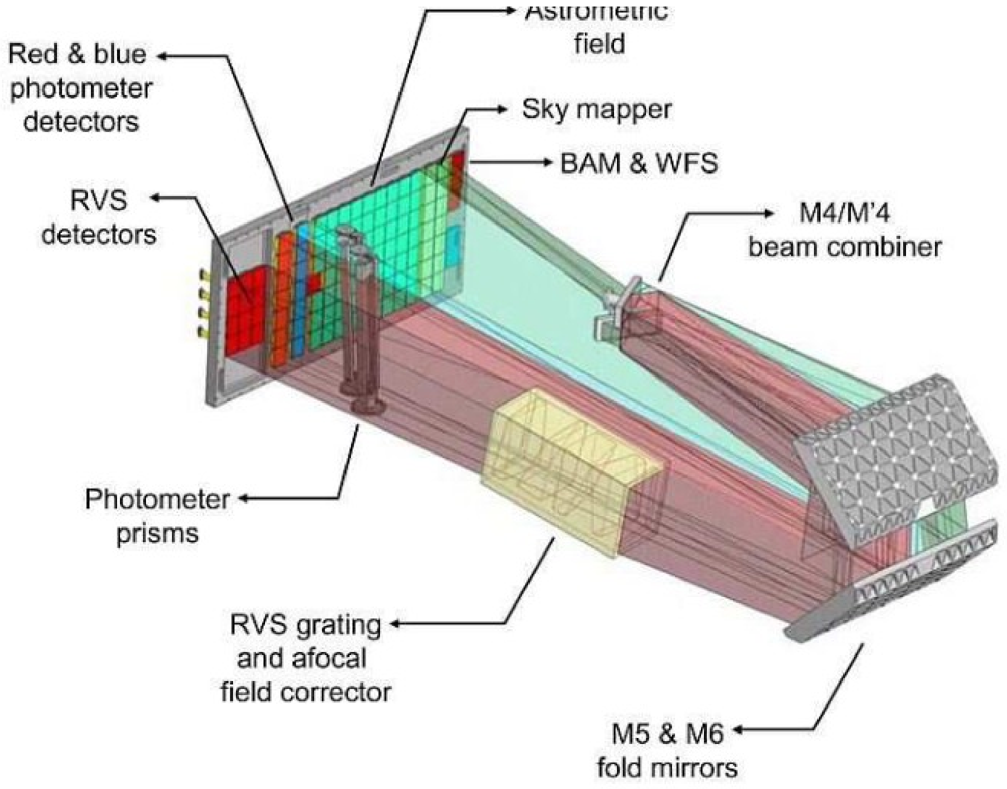
- Sky mapper detect sources for an input catalog (including SNe and asteroids)
- Charges are collected as the sources move across the CCD because of the spacecraft spin
- CCD clocking speed matches the speed of the images in the along-scan direction
- Integration time per CCD is 4.42 s (4500 TDI lines along-scan)
- 12 special electrodes (TDI gates) activated in case of bright objects (to reduce integration time)



(Gaia collaboration 2016)

Photometry and spectroscopy

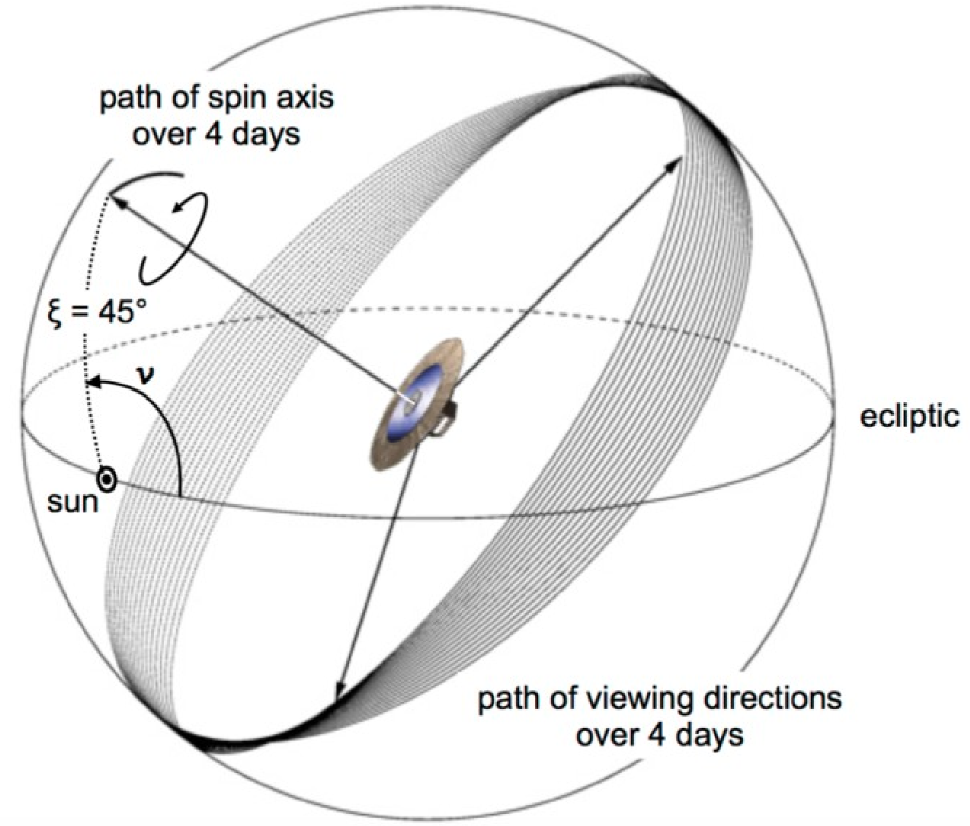
- Two prisms disperse light entering their field of view
  - BP (blue photometer): 330−680 nm
  - RP (red photometer): 640−1050 nm
  - Each illuminate 7 CCDs
- Radial velocity spectrometer (RVS)
  - Integral-field spectrograph
  - Blazed-transmission grating plate (in order 1)
  - Four fused-silica prismatic lenses
  - Interference bandpass-filter plate to limit the wavelength 845–872 nm



(Cropper & Katz 2010)

Scanning law and orbit

- Spacecraft pointing as a function of time
- Maximise the uniformity of the sky coverage
- Fixed spin rate (60 arcsec/sec)
- Fixed solar aspect angle (for thermal stability and parallax sensitivity)
- ~63 days precession period
- Periodic orbit maintenance manoeuvres to remain at L2
- Micro-propulsion subsystem (MPS) for fine attitude control (limits lifetime to 10 \pm 1 years)
- 1 year of reverse precession from July 2019 (6 months of data to be included in DR4)



(Gaia collaboration 2016)

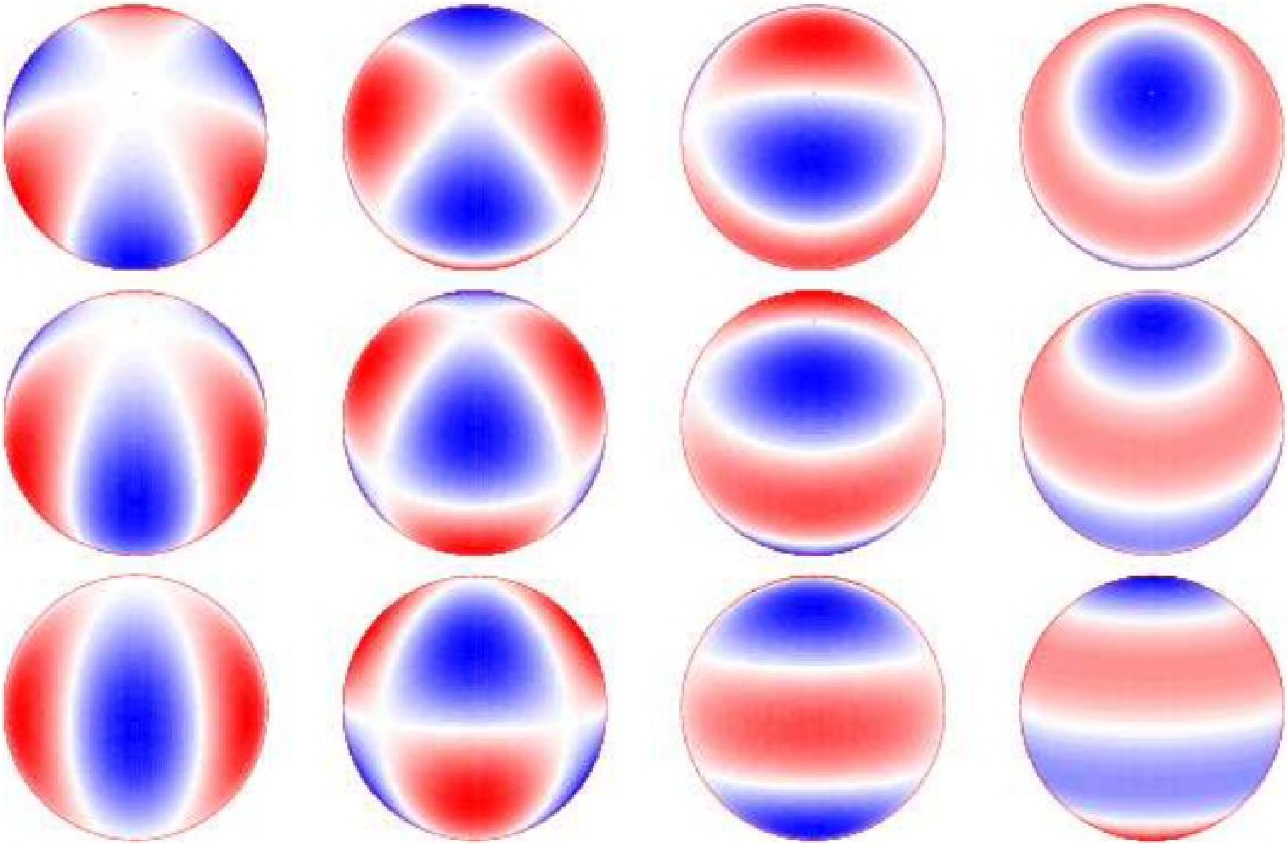
Gaia DR3 (Q2 2022)

	# sources in Gaia DR3	# sources in Gaia DR2
Total number of sources	**1,811,709,771**	**1,692,919,135**
	Gaia Early Data Release 3	
Number of sources with minimally 5 astrometric parameters	1,467,744,818	1,331,909,727
Number of 5-parameter sources	585,416,709	
Number of 6-parameter sources	882,328,109	
Number of 2-parameter sources	343,964,953	361,009,408
Gaia-CRF sources	1,614,173	556,869
Sources with mean G magnitude	1,806,254,432	1,692,919,135
Sources with mean G_{BP}-band photometry	1,542,033,472	1,381,964,755
Sources with mean G_{RP}-band photometry	1,554,997,939	1,383,551,713
	New data in Gaia Data Release 3 (pending validation)	
Sources with radial velocities	≈ 33,000,000	7,224,631
BP/RP spectra	> 100,000,000	-
RVS spectra	≈ 1,000,000	-
Variable source classifications	≈ 13,000,000	550,737
Object classifications	≈ 1,000,000,000	-
Sources with astrophysical parameters	≈ 500,000,000	161,497,595
Non-single stars	≈ a few 100,000	-
QSO host and galaxy morphological characterisation	≈ a few 1,000,000	-
Solar system objects	≈ 150,000	14,099
Reflectance spectra for solar system objects	≈ 50,000	-
Average BP/RP reflectance spectra of asteroids	≈ 10,000	-
Gaia Andromeda Photometric Survey (GAPS)	≈ 1,000,000	-

Questions?

(Credit: Shutterstock)

Asteroseismology



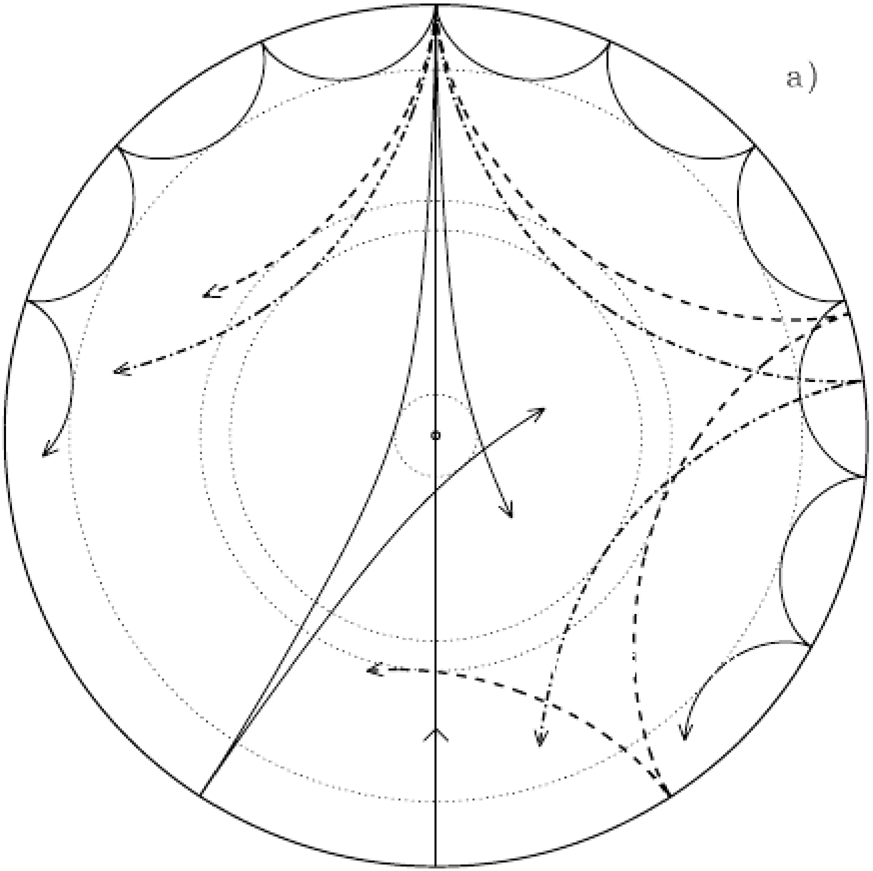
(Kurtz 2006)

Today

1. Asteroseismology
2. TESS
3. PLATO

What is asteroseismology?

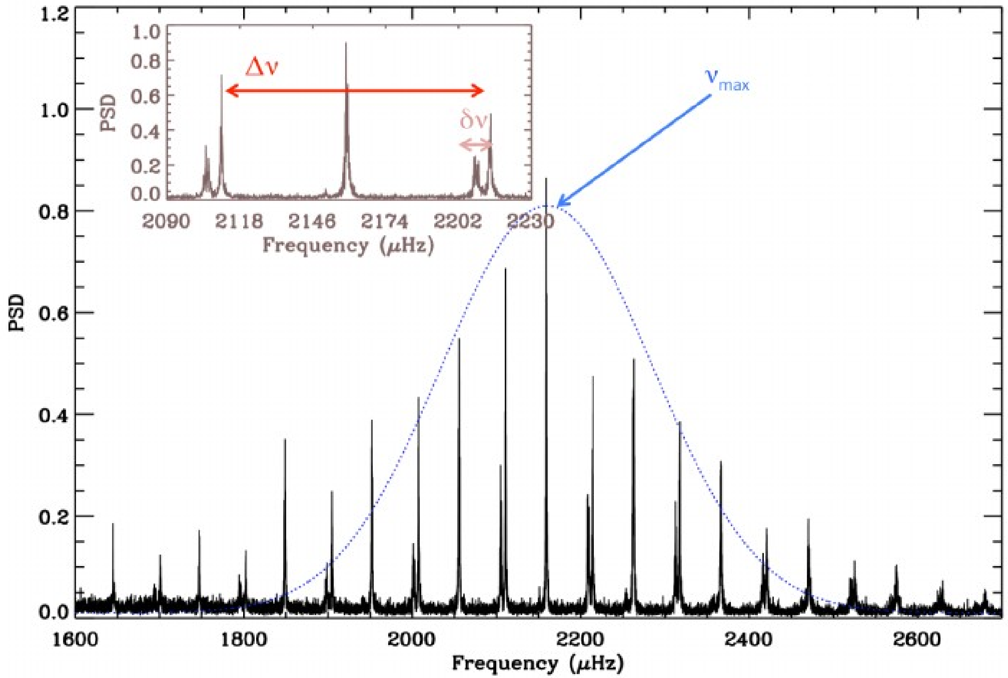
- Study of internal structure of stars using their oscillations
- Oscillations compress and expand the photosphere, causing temperature changes
- These cause brightness variations and movements of the material
- Photometry to measure changes in flux and spectroscopy for Doppler shifts
- But the effects are very small!
- Changes of 10^{-3} K cause 15 cm/s Doppler shifts and changes of 3×10^{-6} in brightness
- How can we measure those??



(Aerts et al. 2010)

Precision!

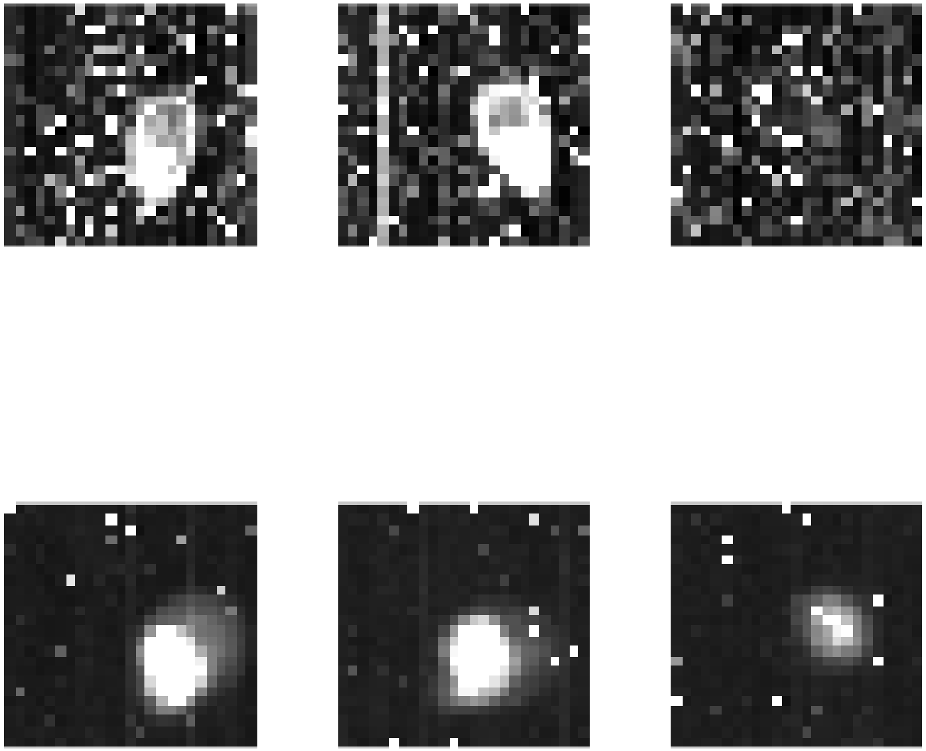
- We do not need to know the stellar temperature to 10^{-3} K, we need to measure the variations
- Precision is needed, not accuracy
- The amplitude of the variations is important, not the zero point of the measurement
- Time series subject to Fourier frequency analysis (see Handler 2013)
- What affects the measurements:
  - Duty cycle: fraction of time observing
  - Sampling time: max exposure time
  - Background noise
  - Total duration of the observations



(Garcia 2015)

Photometry

- Several objects can be observed at the same time
- But ground-based observations are severely limited by scintillation
    - ➔ Random variations in the intensity of the light because of the atmosphere
- Apertures > 50m needed from the ground
- Solution: go to space! (also removes the day/night cycle)
- Examples: WIRE, MOST, BRITE
- Photometry with defocused light over several pixels: precise photometry not sharp imaging



(BRITE PSF: Popowicz 2018)

Spectroscopy

- High-precision spectrographs: single object
- High SNR with high spectral resolution can be hard; limit to bright objects
- But more modes can be detected (for the Sun, the granulation background is larger in intensity)
- HARPS: R~120000, high RV stability, precise wavelength calibration
- Instrument networks around the globe to improve duty cycle
- BiSON (Chaplin et al. 1996): Potassium line at 770nm using a vapour cell in a magnetic field
- GONG (Harvey et al. 1996): Nickel line at 677nm with a polarizing interferometer

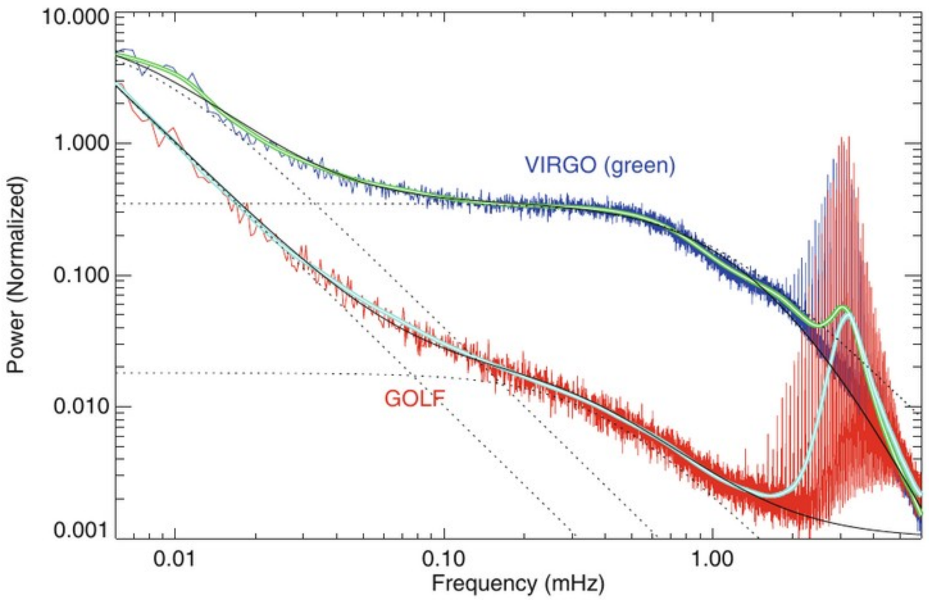
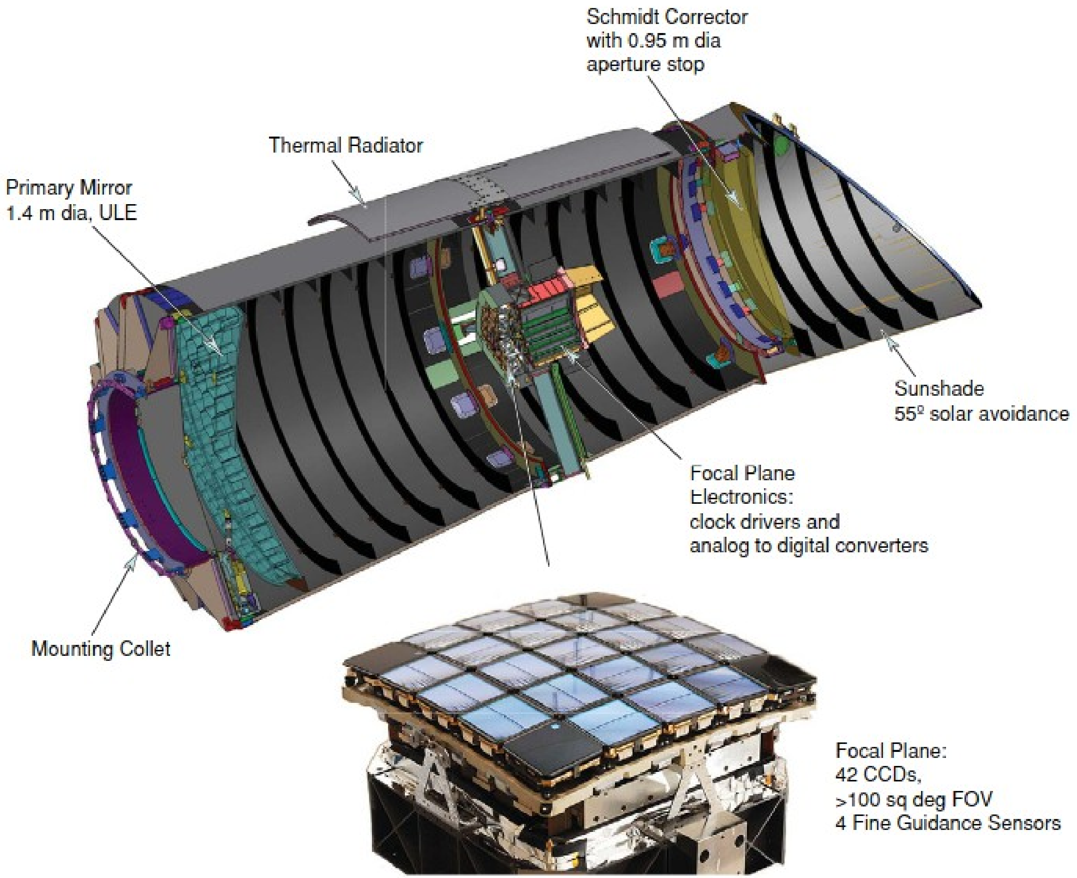


Fig. 4.1. Frequency spectra of the Sun derived from the VIRGO (photometry) and GOLF (spectroscopy) experiments onboard SOHO. Figure courtesy of Hans Kjeldsen.

(Aerts et al. 2010)

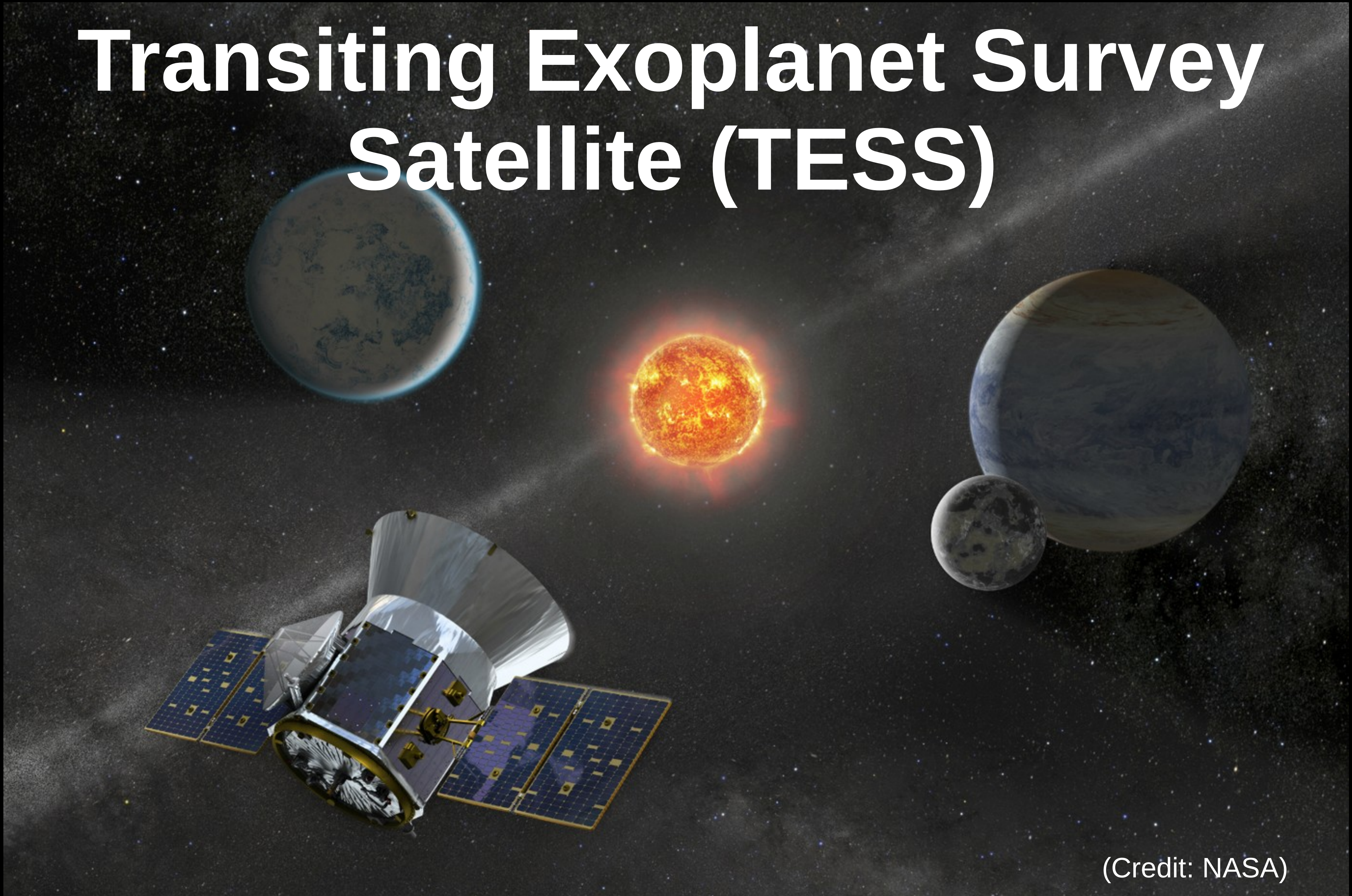
CoRoT and Kepler

- Planet search missions also useful for asteroseismology (precision requirements are similar)
- **CoRoT:** launched December 2006
  - Off-axis telescope with 30cm aperture, FoV 2.8deg x 2.8deg
  - Two channels with two CCDs each: (asteroseismology, planet finding)
- **Kepler:** launched March 2009
  - Schmidt camera, 0.95m corrector lens, 1.4m primary mirror
  - 16deg diameter FoV; 42 CCDs



(Koch et al. 2010)

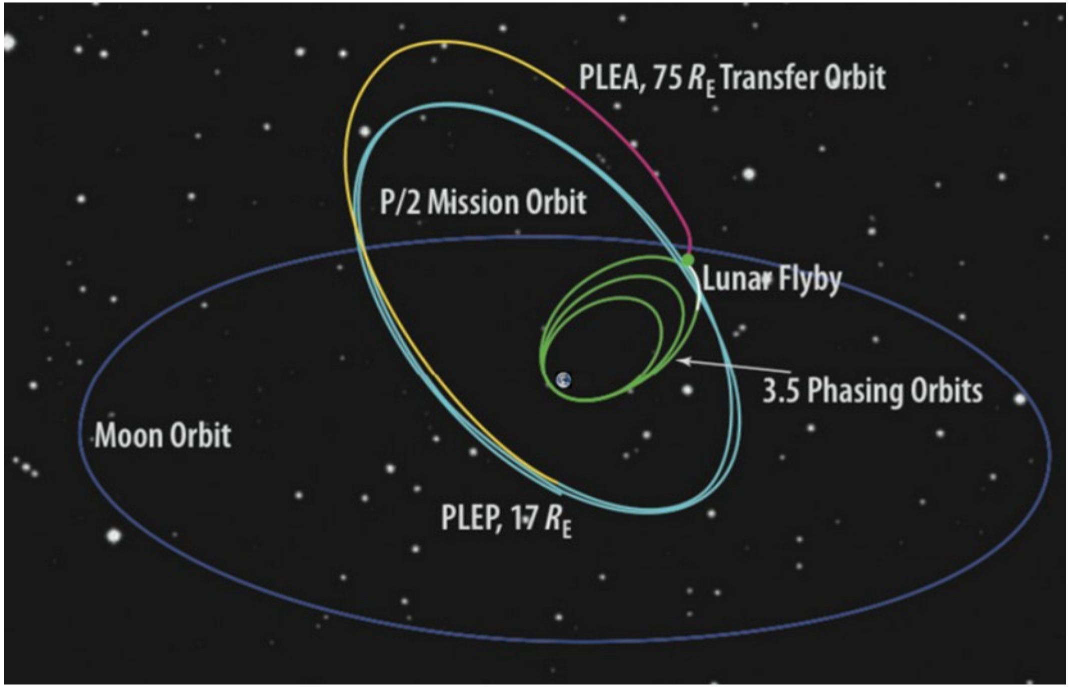
Transiting Exoplanet Survey Satellite (TESS)



(Credit: NASA)

TESS

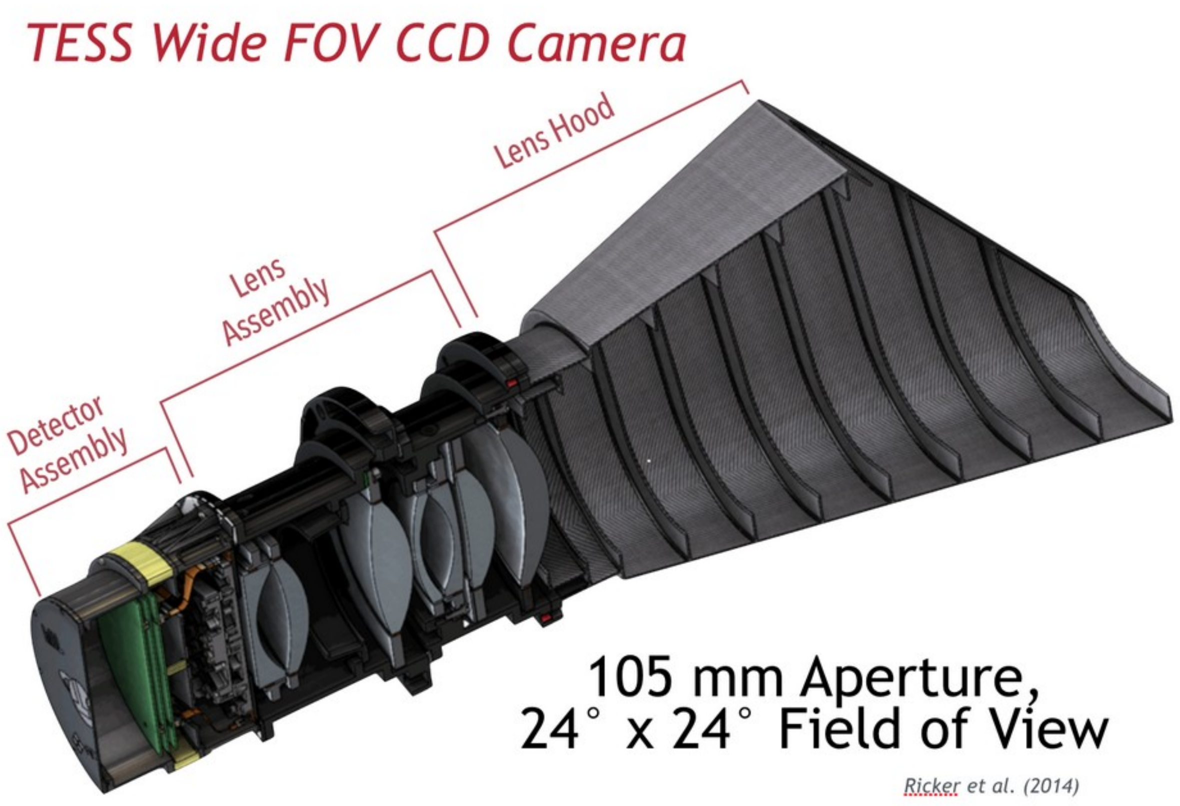
- Launched April 2018. Elliptical high Earth orbit
- Near all-sky survey to search for planets transiting nearby stars.
- Discover planets smaller than Neptune around bright stars
- 2-years primary mission: monitoring ~200 000 main sequence stars (2min cadence)
- 2-years extended mission since July 2020 (with >80% time in Guest Investigator Program – cadence 20s and 2min)
- 3-years second extension from September 2022 (https://heasarc.gsfc.nasa.gov/docs/tess/proposing-investigations.html)



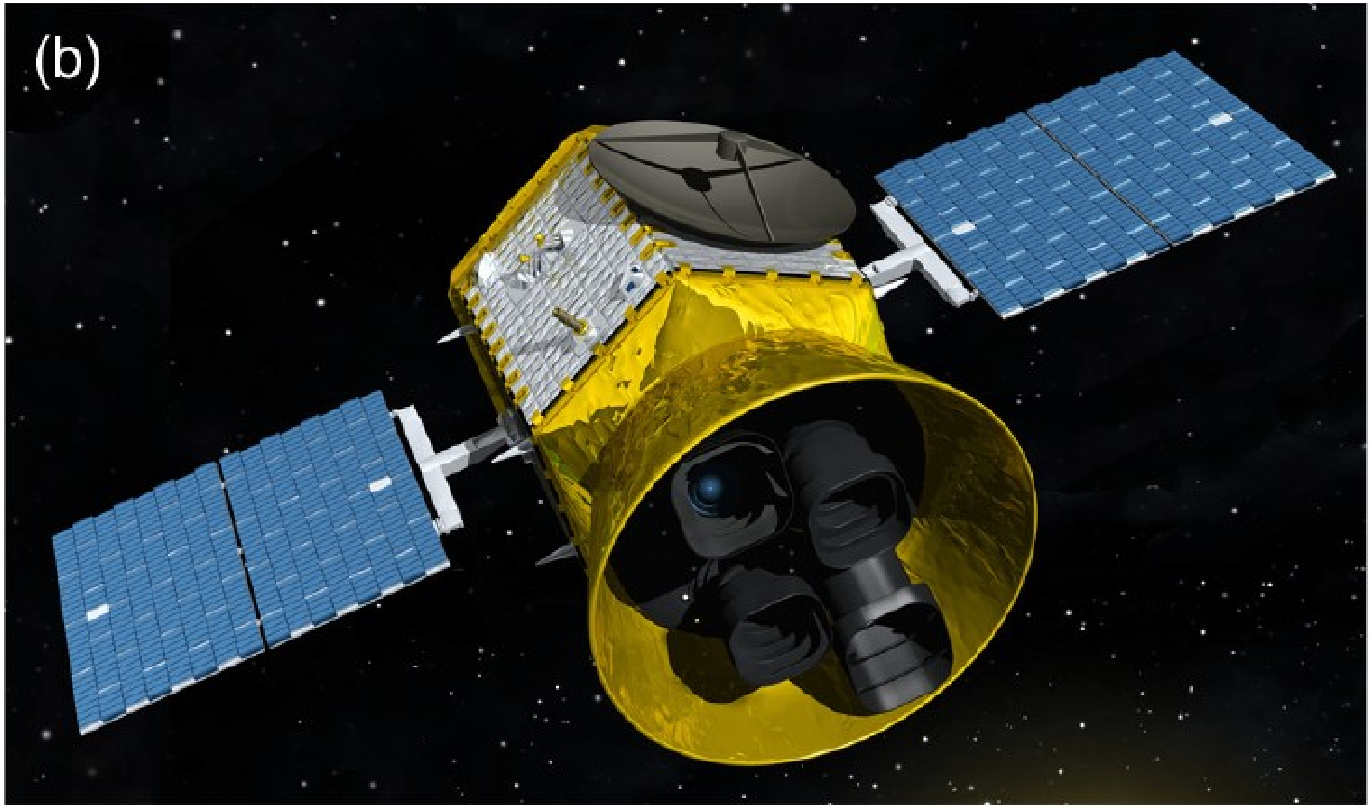
(Ricker et al. 2015)

TESS Telescope

- Four identical cameras, each with:
  - 10.5cm entrance aperture
  - 24deg x 24deg FoV
  - Mosaic of 4 frame-transfer back-illuminated CCDs (2kx2k)
- Exposure times of 2 seconds, summed in groups of 60 (2min)
- Only 10x10 pixels around pre-selected objects stored and transmitted
- One full-frame image saved every 30min

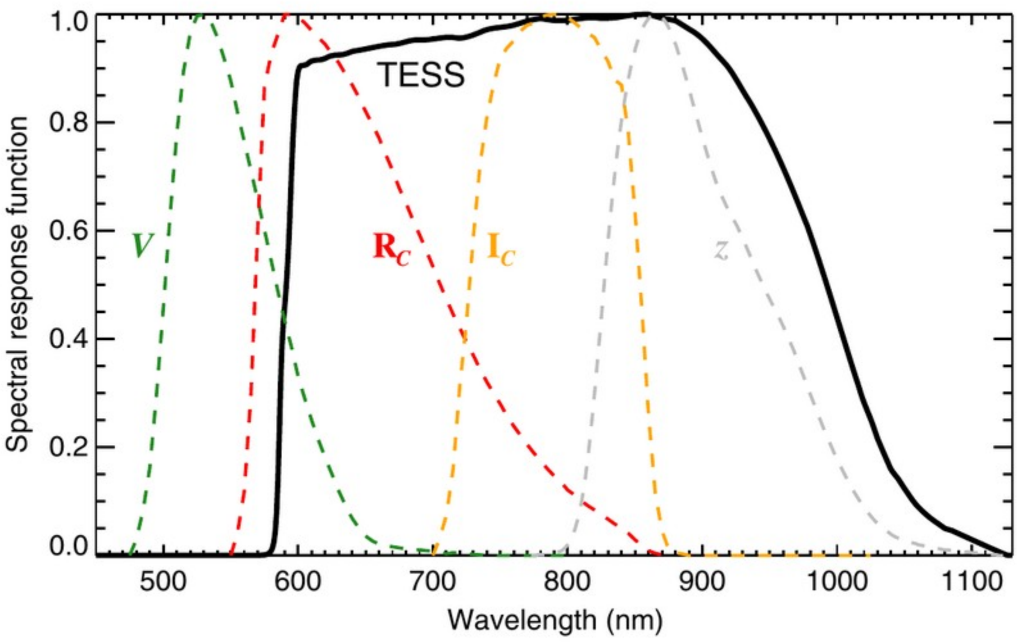


TESS Telescope



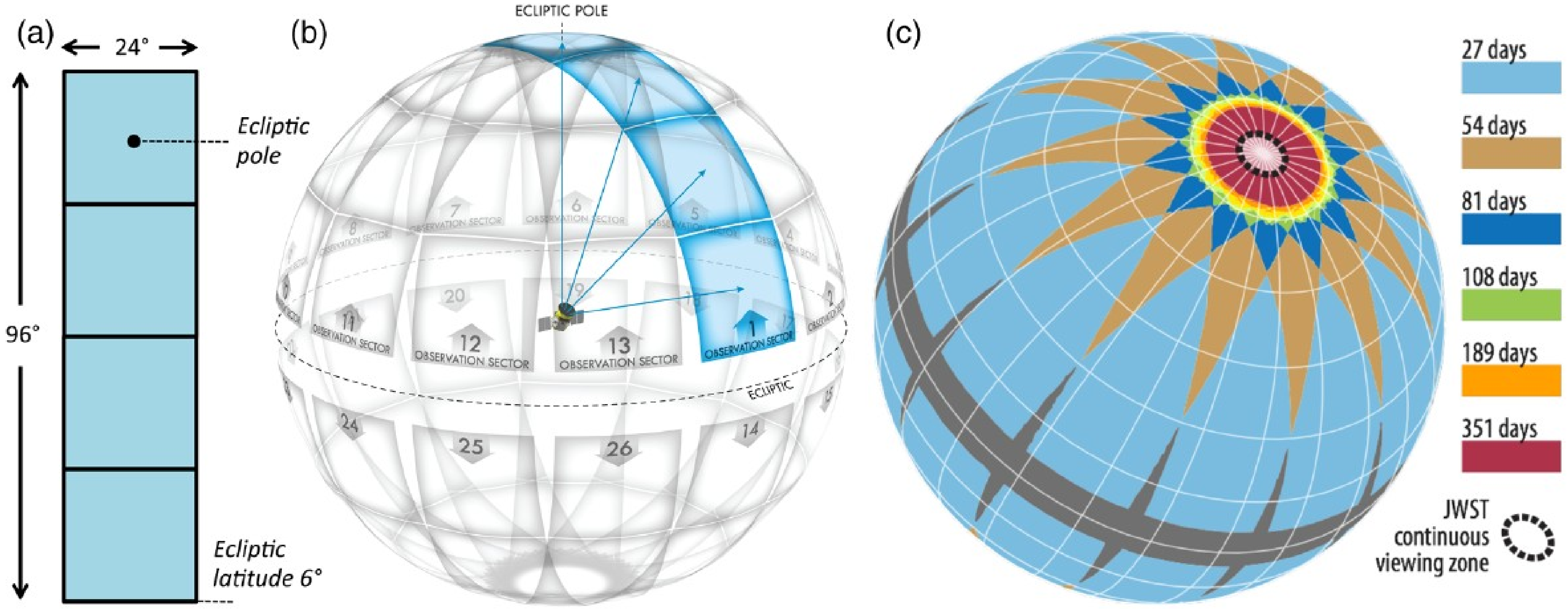
Strategy

- Preferred targets are cool, red stars
- TESS bandpass: wide (reduce photon counting noise) but centred in the red (600-1000nm)
- One lens with a coating that enforces the 600nm cut-off
- Orbit with >300h of unbroken observations
- 4 cameras cover 24deg x 96deg. Observations from 6deg of ecliptic latitude to the ecliptic pole
- One (of 13) sector observed continuously for 2 orbits (27.4 days)
- One hemisphere takes 1 year. Whole sky in 2 years



(Ricker et al. 2015)

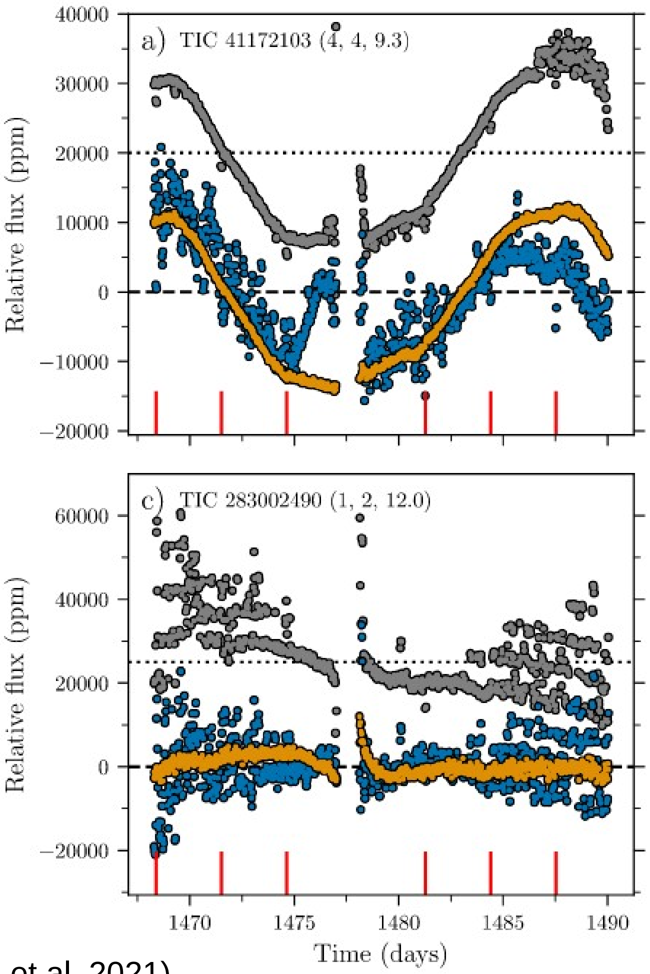
Strategy



(Ricker et al. 2015)

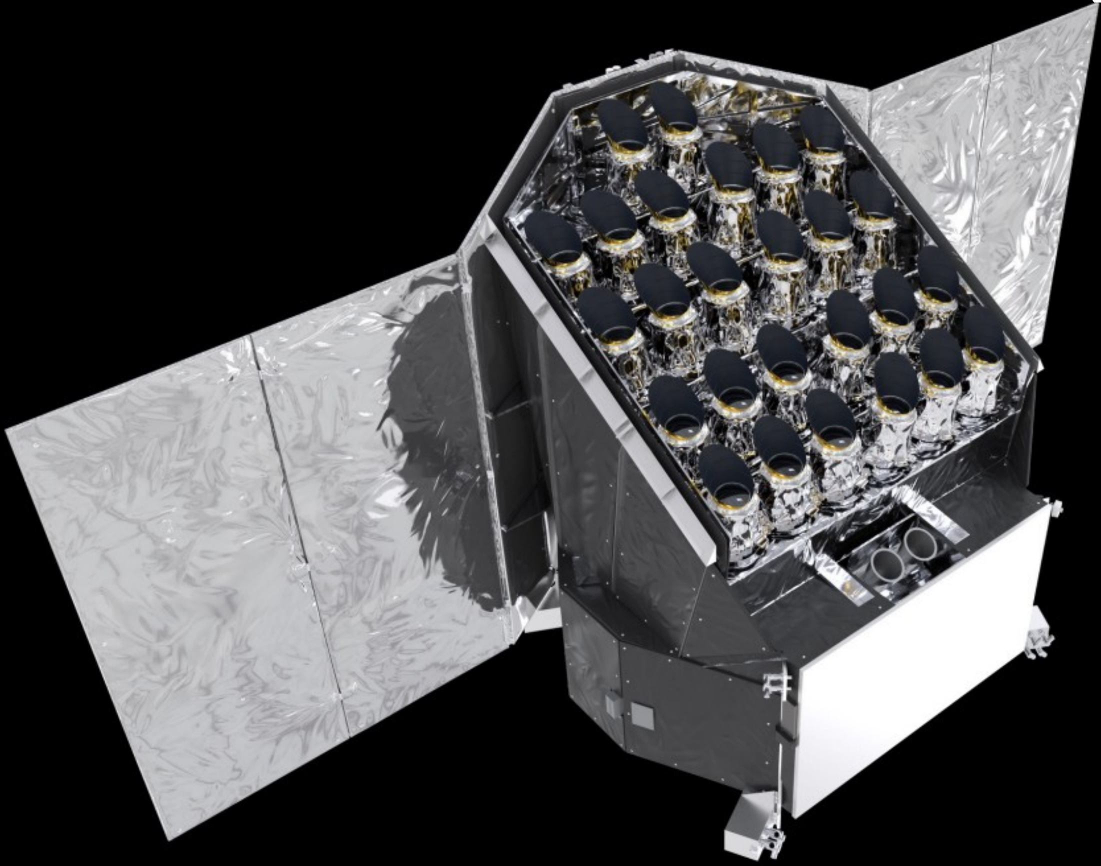
Asteroseismology with TESS

- TESS expected to detect p-modes in 6000 stars brighter than V = 7.5 mag
- All-sky coverage, fine time sampling
- More stars that are brighter and closer to Earth compared to Kepler and CoRoT (good parallaxes, good for RVs and interferometry)
- TESS Asteroseismic Science Consortium (TASC)
- TESS Data For Asteroseismology Lightcurves (TASOC)
- Light curves for all stars, at all cadences, down to a TESS mag ~ 15 (Handberg et al. 2021)
- Guest investigator proposals: Deadline March 18, 2022 (September 2022 – September 2023; sectors 56-69).



(Lund et al. 2021)

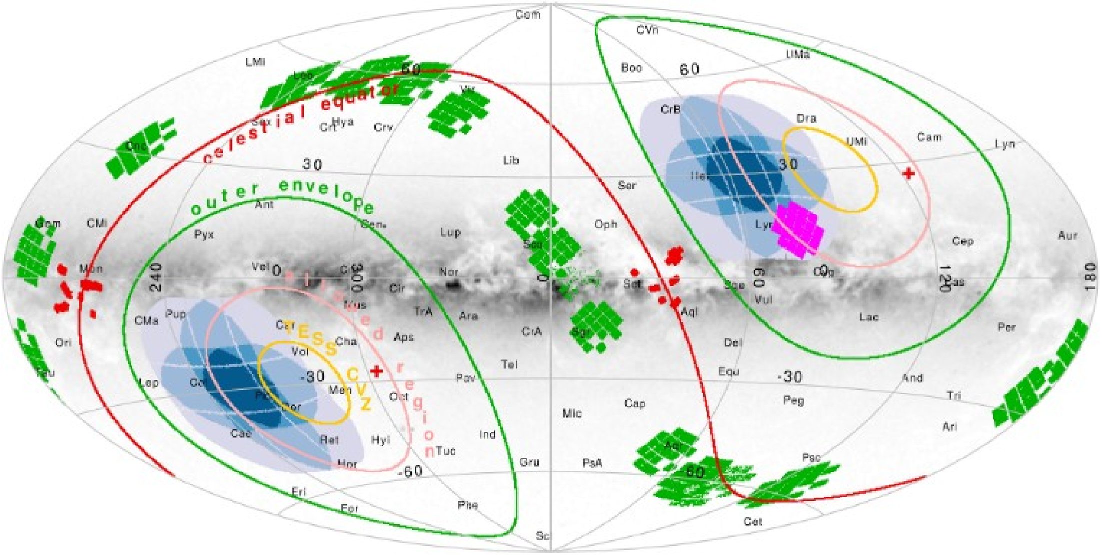
Planetary Transits and Oscillations of Stars (PLATO)



(Credit: ESA/ATG medialab)

PLATO (launch 2026)

- Large amplitude libration orbit around L2
- Detection of terrestrial exoplanets, including planets in the habitable zone of Sun-like stars
- High precision, long (two years), uninterrupted photometry of bright (V ≤ 11-13 mag) stars
- In-orbit lifetime of 6.5 years (consumables for 8 years)
- Two fields monitored for two years each. Optionally split into 3 years long duration pointing and 1 year “step-and-stare” phase
- Guest Observers (GOs) selected by ESA through calls for proposals: complementary science of objects in PLATO sky fields



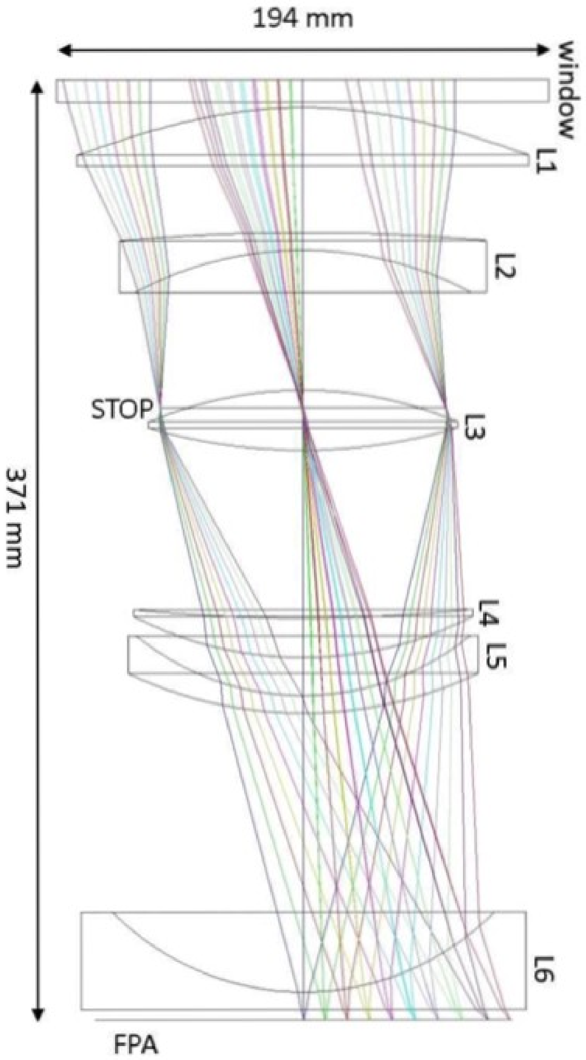
Blue: Provisional PLATO LOP fields; red: CoRoT; Magenta: Kepler; green: K2; yellow: TESS CVZ

(Nascimbeni et al. 2022)

PLATO Telescopes

- 26 cameras (24 normal; 2 fast)
  - 120mm entrance aperture
  - 18.9deg diameter FoV (~14% vignetting at the edges)
  - Mosaic of 4 CCDs (4kx4k)
  - Frame-transfer CCDs in the fast cameras for pointing
  - Flat surface of L1 coated to work as filter (one blue 505-707nm, one red 665-1000nm)
- Wavelength range 500-1000 nm
- Plate scale: 15 arcsec/pixel
- PSF within 9 pixels

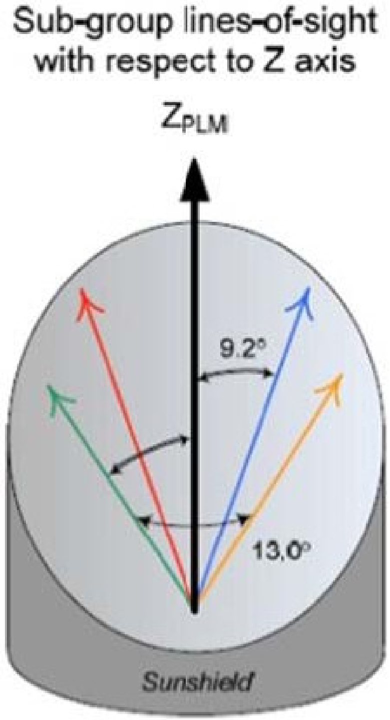
(Magrin et al. 2020)

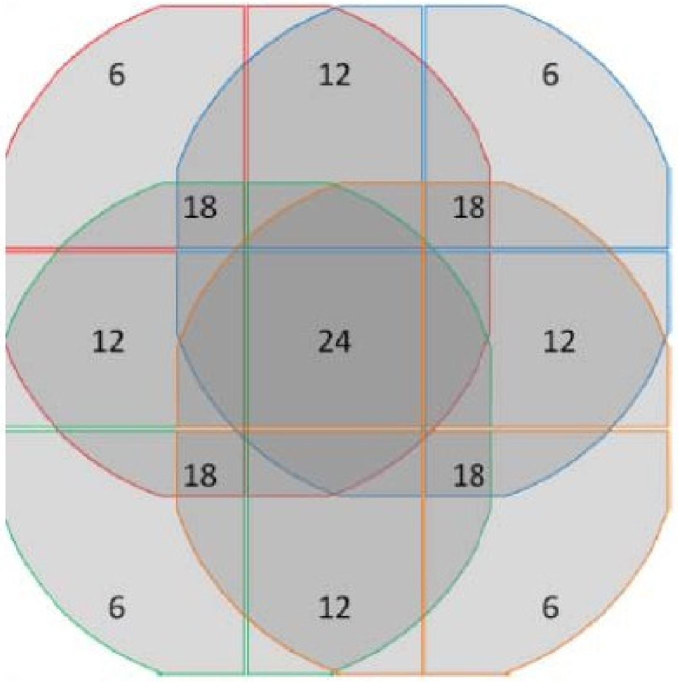


(Credit: ESA)

Observation strategy

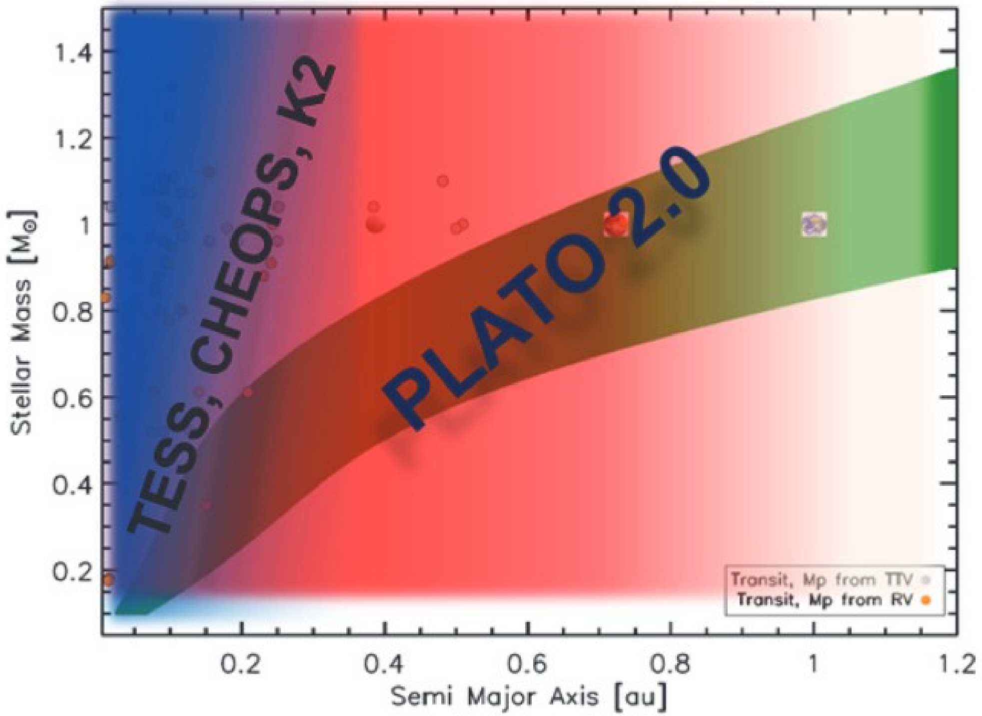
- Groups of 6 cameras have the same FoV
- Variable number of cameras per region of FoV
- Survey a total field of about 2232 deg^2 per pointing
- 25s cycles (22s of exposure time)
- Long-duration pointings: small planets and habitable zone of solar-like stars
- Short pointings: shorter-period planets and galactic exploration





PLATO Science

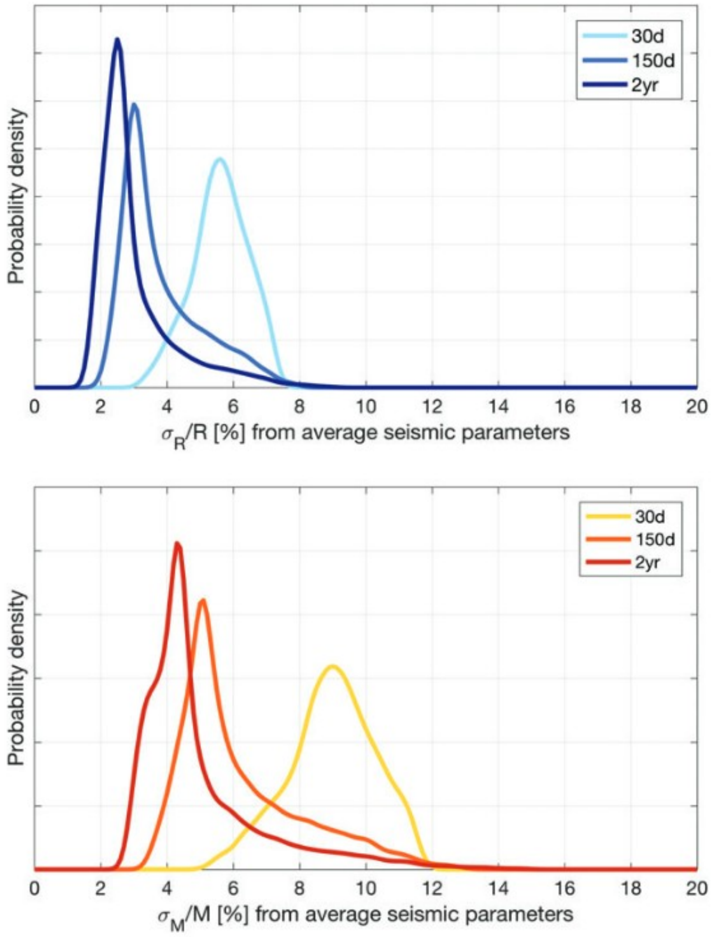
- Data products:
  - Level 1: calibrated stellar light curves and centroids for all bright targets
  - Level 2: planetary transit candidates, asteroseismic analysis, stellar rotation, stellar activity, masses, radii and ages of stars, confirmed planetary systems through Transit Time Variations (TTVs)
  - Level 3: confirmed planetary systems, fully characterised by combining the planetary transits, the seismology of the stars, and ground-based observations
- Public release of L0, L1 and L2 products: one year after the L1 products validated



(PLATO Definition Study Report)

Asteroseismology with PLATO

- Designed for using asteroseismology to characterise planet host stars
- PLATO focus on bright stars: synergy with Gaia and ground-based spectroscopy
- Ocillation frequencies: 15 000 dwarf and subgiant stars with $V \leq 11$
- Light curves: >300 000 stars with $V \leq 13$
- Frequencies with 1σ error of 0.1 μHz for thousands of stars
- Stellar mass to better than 10%, stellar radii to 1–2% precision, stellar ages to 10% precision (Sun with V = 10 mag)



(Miglio et al. 2017)

Questions?

(Credit: Shutterstock)

REFERENCES

- Aerts et al. 2010 (Asteroseismology)
- Chaplin et al. 1996 (SoPh, 168, 1)
- Garcia 2015 (EAS, 73, 193-259)
- Handberg et al. 2021 (AJ, 162, 170)
- Handler 2013 (Asteroseismology)
- Harvey et al. 1996 (Sci, 272, 1284)
- Koch et al. 2010 (ApJ, 713, L79)
- Kurtz 2006 (CoAst, 147, 6)
- Lund et al. 2021 (ApJS, 257, 53)
- Magrin et al. 2020 (Proc. SPIE 11443, 1144312)
- Miglio et al. 2017 (AN, 338, 644)
- Nascimbeni et al. 2022 (A&A, 658, A31)
- Popowicz 2018 (Proc. SPIE, 10698, 1069820)
- Ricker et al. 2015 (JATIS, 1a4003)