

A European Roadmap for Exoplanets

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EPRAT

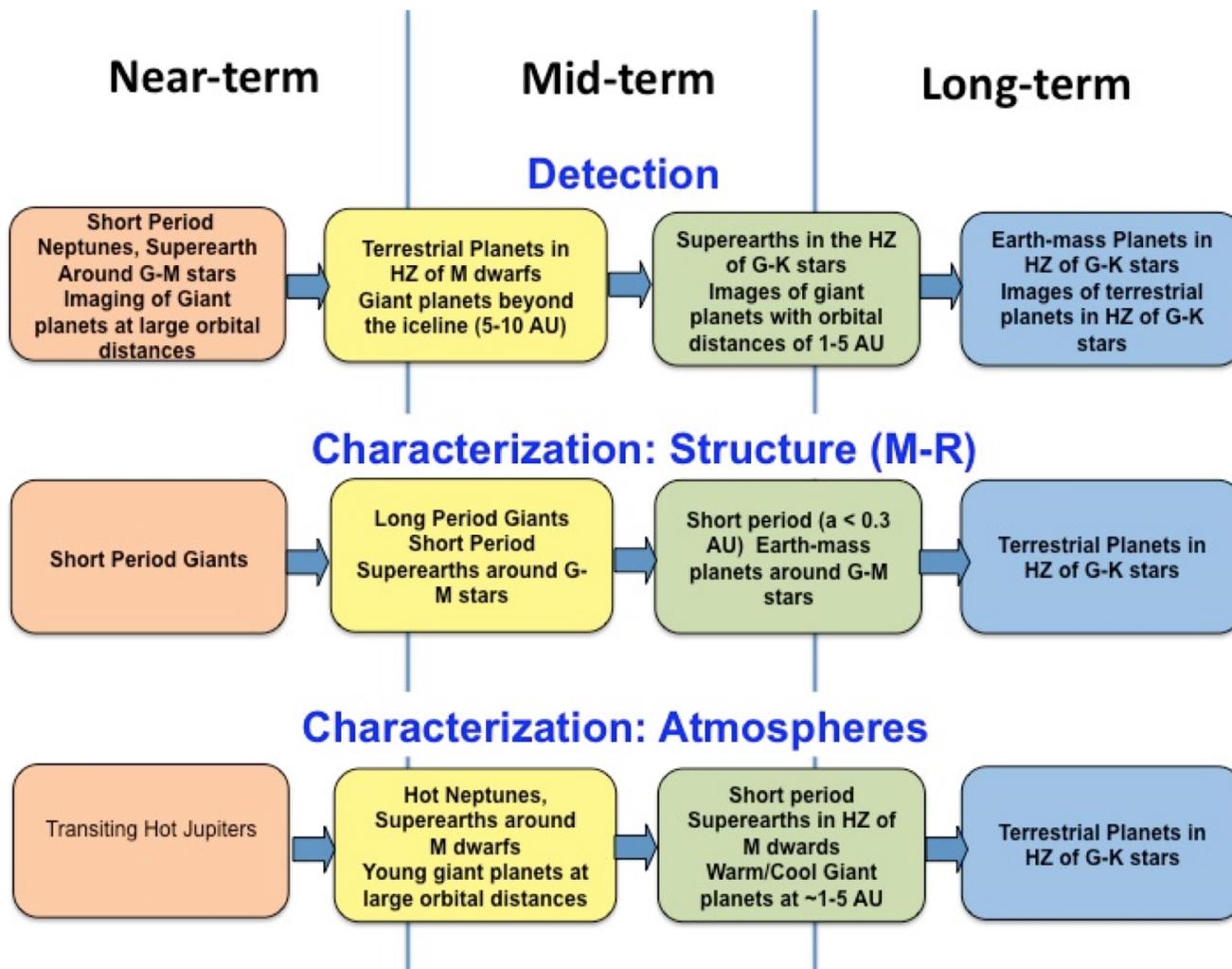
- The main scientific areas covered by the roadmap are:
 - The detection of exoplanets
 - The characterization of their internal structure
 - The characterization of their atmospheres including biosignatures

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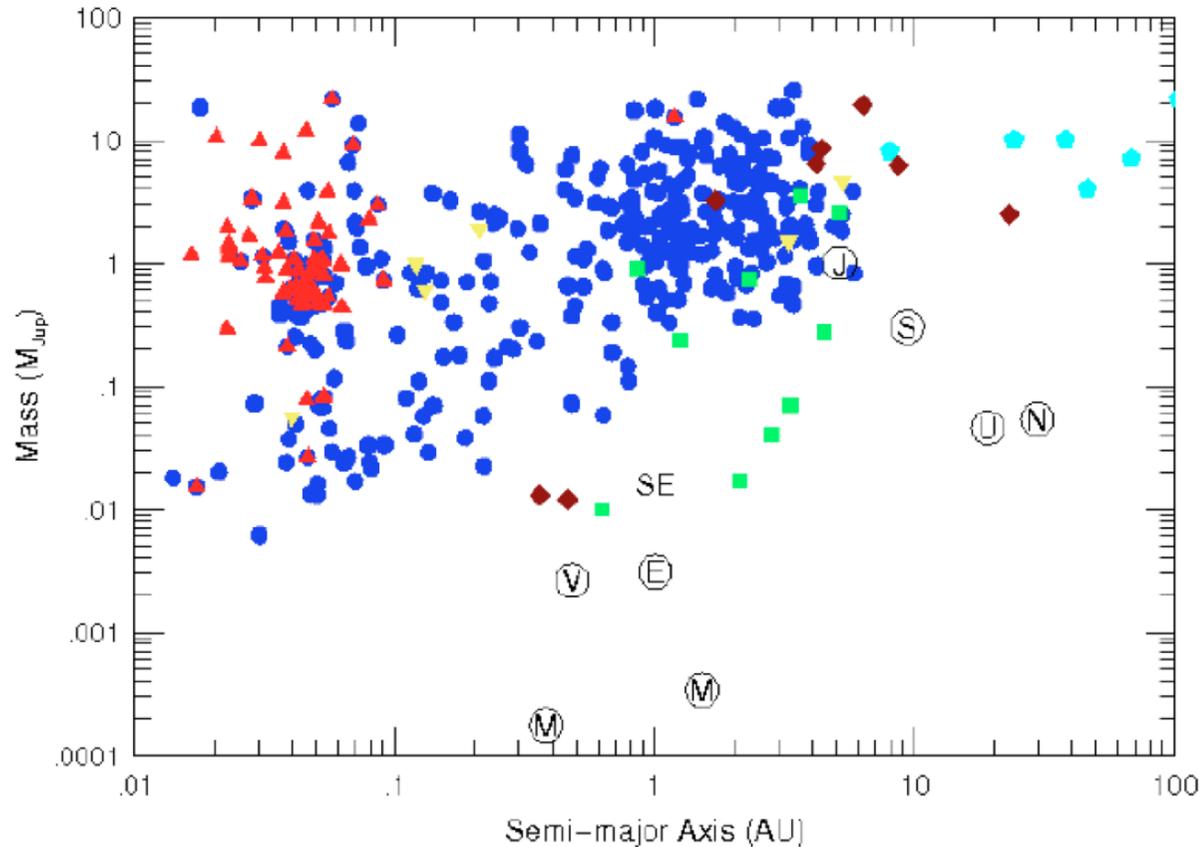
- ESA issued a Call for White Papers from the scientific community in May 2008; a total of 25 White Papers were received. These were evaluated and used by the EPR-AT.
- The Advisory Team met in a series of meetings between September 2009 and January 2010.
- The roadmap effort was presented at several international conferences September to October 2009.
- An open workshop of the community was held 7-8 April 2010 at University College, London, U.K attended by > 60 members of the community. The draft of the roadmap was discussed in parallel discussion groups.
- A final meeting of the advisory team after the workshop took into account the input of the workshop.

EPRAT - members

- Anthony Boccaletti, Observatoire de Meudon, France
- Rudolf Dvorak, Institute for Astronomy, University of Vienna, Austria
- Artie Hatzes, (Chair), Thüringer Landessternwarte, Germany
- Giusi Micela, INAF - Osservatorio Astronomico di Palermo, Italy
- Alessandro Morbidelli, Observatoire de la Cote d'Azur, France
- Andreas Quirrenbach, Landessternwarte, Heidelberg, Germany
- Heike Rauer, German Aerospace Center (DLR), Germany
- Franck Selsis, Laboratoire d'Astrophysique de Bordeaux (LAB), France
- Giovanna Tinetti, University College London, United Kingdom
- Stephane Udry, Université de Genève, Switzerland
- Anja C. Andersen, Dark-Cosmology Center, Copenhagen, Denmark



We addressed objectives in a near-, mid- and long-term scenario, as well as “3-lanes” of detection, characterization of internal structure (mass, radius, mean density) and the characterization of spectral atmospheres. Near term is approximately 2011-2017, Mid-term 2015-2022, and Long-term beyond 2010.



Exoplanet discoveries from the various search methods in the Mass-Semi-major axis plane. Blue dots: Radial velocity detections; Red triangles: Transit detections; Inverted yellow triangles: astrometric detections; Green squares: Microlensing detections; Blue Pentagons: Imaging detections; Red diamonds: Timing detections. The letters mark the location of the planets in the solar system. “SE” denotes a Super earth with $5 M_{\text{Earth}}$.

Detections - methods

- Radial Velocities
- Transits
- Astrometry
- Imaging
- Microlensing
- Timing detections

Characterization

- Fundamental Planetary Parameters (Mass, radius, density, internal structure, orbital parameters)
- Atmospheric Characterization (composition, albedo, thermal structure, biomarkers)
- The solar neighborhood: Understanding our Sample
- Theory

Goals and Key Questions

- Major components:
 - Detections: Completing the mass to semi-major axis parameter space and understanding the architecture of extrasolar planetary systems.
 - Characterization of internal structure: mass, radius, and mean density.
 - Characterization of atmospheres: temperature, albedo, composition and including biosignatures.

Key questions (in order of difficulty)

- **KQ1:** What is the diversity and architecture of exoplanetary systems as a function of stellar parameters and birth environment?
- **KQ2:** What is the diversity of the internal structure of exoplanets?
- **KQ3:** What is the diversity of exoplanetary atmospheres?
- **KQ4:** What is the origin of the diversity and how do planets form?
- **KQ5:** What are the conditions for planet habitability, how common is exo-life and can we detect the biosignatures.

Major goals (1)

- **Detection**
 - Census.
 - Architecture.
 - Targets for characterization studies.
- **Structure**
 - Mass-Radius relationship for exoplanets down to terrestrial mass.
 - Internal structure models of exoplanets (requires good precision in mass and radius determination).
 - Input for formation and evolution models.

Major goals (2)

- Atmospheres
 - Composition of young and old giant planet atmospheres.
 - Composition of terrestrial planet atmospheres.
 - Evolution of exoplanet atmospheres.
 - Bio-signatures and habitability.

Recommendations (1)

ongoing

- **OG-1** *Continue and expand radial velocity searches among several thousand nearby F-K main sequence stars and evolved, intermediate mass stars using optical spectrographs.*
- **OG-2:** *Securing the necessary telescope resources*
- **OG-3:** *Optimizing ground-based transit searches*
- **OG-4** *Theoretical Studies*
- **OG-5:** *Laboratory measurements to produce line lists, atomic and molecular transition probabilities, opacities, and equation of states.*

Near-term Road Markers ~2011-2017 (ground)

- **NG-1:** *Observations of all stars out to 50 pc: understanding the host stars of exoplanet systems, statistics as a function of stellar properties*
- **NG-2:** *Radial Velocity Planet Searches in the Infrared with emphasis on short-period, low mass planets around M dwarfs*
- **NG-3:** *Terrestrial planets in the habitable zone of G-type stars: High cadence monitoring of a sample of 50-100 G-type stars with low levels of activity*
- **NG-4:** *Characterization of Transiting Planets in the visible and IR with ground-based and on-going space based facilities*
- **NG 5:** *Radio studies of Exoplanets*
- **NG-6:** *Ground-based support of CoRoT, Kepler, and preparation for ground-based support for GAIA*
- **NG-7:** *Continue ground-based microlensing searches*
- **NG-8:** *Make Effective use of Planet finders for Exoplanets Studies*
- **NG-9:** *Calibration of giant planet evolutionary tracks*
- **NG-10:** *A study of exo-zodi systems and their influence on direct imaging of terrestrial planets*
- **NG-11:** *An investigation of the influence of stellar activity on habitability and anticipated atmospheric signatures*

Near-term Road Markers ~2011-2017 (space)

- **NS-1:** *Continuation of the CoRoT and Kepler past the nominal mission life*
- **NS-2:** *Characterization of exoplanets with PLATO*
- **NS-3:** *Make effective use of JWST for Exoplanets Studies (spectral characterization, imaging, photometry, phase curves, colors)*
- **NS-4:** *Theoretical studies on the spectroscopic and possible bio-signatures expected from exoplanets covering a wide range of masses (terrestrial to giant planets) and a wide range of temperatures*
- **NS-5** *External Occulters*
- **NS-6:** *Space-based Microlensing Surveys*

Technology Recommendations

~2011-2017

- **NT-1** *Improved wavelength calibration for radial velocity measurements*
- **NT-2**: *Detector Development*
- **NT-3**: *Technological studies for the direct imaging and spectroscopy of exoplanets*

Anticipated milestones at end of term:

- Detections
 - ~1000 exoplanets around host stars with stellar masses $0.1 - 2 M_{\odot}$
 - ~100 multiple systems
 - A few super earths ($5-10 M_{\text{Earth}}$) at 1 AU from G-type stars
 - Tens of Terrestrial planets ($1-5 M_{\text{Earth}}$) in the habitable zone of M dwarfs
 - The first estimate of f_{Earth} , the estimated fraction of stars with terrestrial planets in the habitable zone of stars
 - Direct detections (imaging) of up to tens of Giant planets at semi-major axis $a > 10$ AU
- Characterization of the Internal Structure
 - Mass-Radius relationship of giant planets with $a < 0.5$ AU
 - Mass-Radius relationship of super earths ($5-10 M_{\text{Earth}}$) with $a < 0.1$ AU
- Characterization of Atmospheres
 - Spectra of tens of giant planets with $a < 0.05$ AU
 - Spectra of a few giant planets and super planets (mass = $5-20 M_{\text{Jup}}$) at $a > 10$ AU
- Technological
 - Low noise Infrared Detectors
 - Doppler precision $\sim 10 \text{ cm s}^{-1}$
 - Assessment of various direct detection (angular resolved) methods: coronagraphs, nulling interferometer, occulters

Mid-term roadmarkers ~2015-2022 (ground)

- **MG-1:** *Secure the ground-based support necessary for follow-up of PLATO transit candidates*
- **MG-2:** *Use of Atacama Large Millimeter Array (ALMA) to study exoplanets in their birth environment*
- **MG-3:** *Continue direct imaging studies from the ground (AO, coronagraphy) to find large planets at large orbital distances*
- **MG-4:** *Obtain a sample of Terrestrial planets in the Habitable Zone of G-K type stars*

Mid-term roadmarkers ~2015-2022 (space)

- **MS-1.** *Preparation for an M-class and/or smaller mission for characterization of exoplanet atmospheres from gas giants to Super-Earths*
- **MS-2:** *Transit Searches for Small Planets around solar-type stars*
- **MS-3:** *True mass determination of known giant planets with Gaia: Deriving the true mass function for giant exoplanets*
- **MS-4:** *Obtain accurate stellar parameters using Gaia and PLATO*
- **MS-5** *Devote time on ELT and JWST for key programs in spectroscopy of transiting planets and direct imaging of Giant planets at large orbital distances*
- **MS-6:** *Astrometric Searches for Terrestrial Planets*

Anticipated milestones at end of term:

- Detections
- 2000 exoplanets around host stars with stellar masses $0.1 - 2 M_{\odot}$
- 200 multiple systems
- Tens of Jovian and Neptune planets with semi-major axis, $a > 5$ AU
- ~ 100 -200 candidate terrestrial planets in the Habitable Zone of G-type stars and ~ 10 of these around nearby bright stars \rightarrow Target List for flagship mission
- Good estimate of f_{Earth} , the estimated fraction of stars with terrestrial planets in the habitable zone of stars
- Direct detections (imaging) of up to ~ 100 Giant planets at $a > 10$ AU
- Characterization of the Internal Structure
- Mass-Radius relationship of giant planets with $a < 1$ AU
- Mass-Radius relationship of Terrestrial planets ($1-5 M_{\text{Earth}}$) with $a < 0.1$ AU
- Characterization of Atmospheres
- Spectra of \sim tens of giant planets with $a = 1-5$ AU
- Spectra of a many 10s of Hot Jupiters: $m = 1-3 M_{\text{Jup}}$, $a < 0.1$ AU
- Spectra of terrestrial planets ($1-5 M_{\text{Earth}}$) in the habitable zone
- Expected biosignatures and required instrumentation to detect these
- Technological
- Technology for high contrast imaging suitable for space missions
- Ability to implement this technology in space

Long Term Road Markers (~2020 and beyond)

- The focus of the long-term portion of the roadmap is the characterization of terrestrial planets in the habitable zone of G-type stars
- **Ground Recommendations:**
 - **LG-1:** *An astrometric Search for Giant planets using Gaia combined with RV ground-based follow-up observations*

Long Term Road Markers ~2020 and beyond (Space)

- **LS-1:** *Extend the life of the GAIA mission past its nominal lifetime*
- **LS-2:** *Begin work on a flagship mission to characterise all the known terrestrial planets in the habitable zone of F-K type dwarfs*
- **LS-3:** *Astrometric detections of terrestrial planets with space missions and ground-based ultra-precise RV measurements: This along with LG-1 should complete the mass function of planets down to the low mass end and to fully characterise planetary system architectures*

Expected milestones

- Detections
- Complete census of exoplanets: good sampling of the mass/semi-major axis parameter space from $m = 1 M_{\text{Earth}}$ to $10 M_{\text{Jup}}$ and $a = 0.01 - 10 R_{\text{Jup}}$
- Good understanding of the the structure of Exoplanetary Systems
- Excellent Targets for flagship missions to characterise
- Characterisation of the Internal Structure of exoplanets
- Mass-Radius relationship of giant planets up to $a = 100 \text{ AU}$
- Mass-Radius relationship of Terrestrial planets ($1-5 M_{\text{Earth}}$) with $a < 1 \text{ AU}$
- Characterization of Atmospheres of exoplanets
- Spectra of few of Super-Earths in habitable zone of solar-type stars
- Spectra of terrestrial planets ($1-5 M_{\text{Earth}}$) in the habitable zone of G stars

General recommendations

- **G1:** *International Cooperation/Coordination*
- **G2:** *Better coordination between ESA and ESO.*
- **G3:** *Coordination between ESA, national space agencies, and universities*
- **G4:** *Involve the Planetary Community*
- **G5:** *A Rigorous Public Outreach.*
- **G6:** *Keep a vibrant community going.*

Conclusive recommendations

- With respect to possible future space missions that can be selected under CV, we can identify 3 “high priority “ mission types:
- A mission for the characterization of exoplanetary atmospheres down to Super-Earth masses ($\approx 5 M_{\text{Earth}}$), either as close in planets (transiting systems) or ones at large orbital distances (angularly resolved detections). A space mission that can characterise a wide range of planetary atmospheres will provide a major “boast” to this roadmap path.
- A photometric mission to characterise the internal structure of terrestrial planets. PLATO will largely accomplish this goal and thus this mission has high priority for this roadmap
- An astrometric mission to find terrestrial planets orbiting in their HZ. Astrometry provides a key parameter of exoplanets – their mass. Space-based astrometric measurements have the potential of finding those terrestrial planets which will form the target list for future missions aimed at determining other planetary parameters. Gaia will measure the mass of a large number of exoplanets, but only for giants. SIM-Lite would have done this for terrestrial planets, but its “demise” has left a gap in our roadmap. An astrometric mission with the same precision as SIM-Lite but focussing on exoplanets may achieve the same “exoplanet” goals.