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SUBMILLIARCSECOND ASTROMETRY OF EXOPLANETS AND BROWN DWARFS IN HIGH-CONTRAST IMAGING

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Abstract. Orbital monitoring of exoplanetary systems is fundamental for analyzing their architecture, dynamical stability and evolution, and mechanisms of formation. For directly-imaged exoplanets and brown dwarfs, high-precision relative astrometry is mandatory to measure precisely their slow orbital motion due to the wide separations to the stars (>∼10 au) and their orbital parameters. Relative astrometry at the milliarcsecond level has been achieved with the first dedicated coronagraphic instruments on 8m telescopes (SPHERE, GPI) thanks to the high contrast and angular resolution that they deliver as well as optimized calibration procedures. The high-contrast imaging modes of MICADO, HARMONI, and METIS should achieve submilliarcsecond precisions at closer separations to the stars thanks to the gain in angular resolution and sensitivity provided by the ELT. We discuss the synergies of the ELT with radial velocity surveys, Gaia, GRAVITY+, and SPHERE+ for measuring the orbital plane, mass, and/or luminosity of exoplanets and brown dwarfs close to stars. Such measurements will allow for strong tests of their models of thermal evolution, which are affected by uncertainties in the modeling of the atmosphere and of the accretion process.

Keywords: exoplanets, brown dwarfs, high-contrast imaging, relative astrometry, ELT

1 Introduction

Most of the currently-known exoplanets are detected through indirect methods (radial velocities or RV, primary transits), which do not allow for measuring the light emitted by the planets and for characterizing their atmosphere. Several formation, evolutionary, and atmospheric models have been proposed to explain the extreme diversity of exoplanets in terms of architecture, mass, and composition, and because of uncertainties in the modeling (e.g., clouds, atmospheric opacities, the physics of the accretion process).

Exoplanet models remain poorly tested because it is not possible to measure with a single technique the mass, radius, and/or luminosity. Multitechnique approaches are required but the overlap between the exoplanet detection techniques is still small. The combination between RV and transits has been the most prolific for measuring the mass and radius of exoplanets but it is essentially limited to exoplanets close to the stars and strongly irradiated. Combining RV and high-contrast imaging would provide mass and luminosity measurements of exoplanets at separations beyond 1 au and colder exoplanets. However, the overlap between the techniques is still marginal, with RV biased toward mature exoplanets orbiting stars with low activity and high-contrast imaging biased toward young exoplanets because the thermal emission of exoplanets is larger for younger ages. Absolute astrometry is less sensitive to the stellar activity and can detect planets around young and old stars. This technique has provided very few detections so far because of stringent precision requirements (a few tens of a μas). However, this is expected to change with the exquisite precision of Gaia.

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2 The ELT: an ideal instrument for submilliarcsecond astrometry of directly-imaged exoplanets and brown dwarfs

Thanks to its high angular resolution and sensitivity, the Extremely Large Telescope (ELT) will be an ideal instrument for high-precision astrometry in high-contrast imaging of exoplanets. Assuming a perfect calibration of the instrument systematics, the astrometric precision can be approximated as the ratio of the width of the point-spread function to the signal-to-noise ratio (Lindegren 1978). Assuming that the astrometric precisions of $\sim$1–2 mas achieved with SPHERE scale as λ/D with λ the observing wavelength and D the telescope diameter, we can expect the high-contrast imaging modes of the ELT's first-light instruments, MICADO, HARMONI, and METIS, to reach submilliarcsecond astrometric precisions of $\sim$0.2–0.5 mas. These higher astrometric precisions will be reached at closer separations to the stars compared to SPHERE, down to $\sim$2 au vs. down to $\sim$10 au.

Currently, MICADO is the only ELT instrument designed for high-precision astrometry for the study of the Galactic Center and stellar clusters (50 μas with a goal of 20 μas, see Clénet et al., this volume). However, high-contrast imaging of exoplanets requires a dedicated strategy to calibrate the position of the star (masked by coronagraphy) and the orientation of the field to the North (use of pupil-tracking observations to fix the stellar aberrations on the detector to calibrate them).

2.1 Synergies with RV surveys and Gaia

High-contrast imaging of exoplanets presents strong synergies with RV surveys and Gaia. A major result of high-contrast imaging surveys such as the SPHERE/SHINE survey (Desidera et al. 2021; Langlois et al. 2021; Vigan et al. 2021) is that giant exoplanets at separations beyond 10 au from solar-type stars are rare (about a few %). This result is coherent with the poor efficiency to form planets in wide orbits predicted for the planetary formation model by core accretion (which is the most accepted mechanism for forming the planet population detected at close separations with RV and transits). It also implies that alternative planetary formation models proposed to form planets in wide orbits such as the disk gravitational instability model occur rarely. The stars which were observed in these high-contrast imaging surveys were mostly selected based on age criteria and in some cases the presence of an infrared excess indicating the presence of a circumstellar disk. To improve the detection rates of high-contrast imaging surveys, the main path explored is to reach closer separations to the stars, where the bulk population of exoplanets is located. This requires to improve the performance at small angular separations of current instruments on 8m telescopes (e.g., SPHERE+, GPI2.0) or to build larger telescopes such as the ELT. A second approach is targeted imaging of stars showing indirect signs of the presence of long-period companions in RV or absolute astrometry. Such targeted surveys have shown detection rates of $\sim$30% (Currie 2020). For companions only detected in RV or from an astrometric acceleration trend, high-contrast imaging is valuable to measure their orbital inclination and mass. The least massive companions detected so far are in the brown dwarf regime, but the prospects are promising with the upcoming publication of the catalog of exoplanets detected by Gaia.

Another strong synergy between high-contrast imaging with RV surveys and Gaia deals with the characterization of the detected companions. The theoretical mass-luminosity-age relations used in high-contrast imaging to estimate the mass of the detected companions are poorly calibrated because we have very few empirical mass measurements of young and/or low-mass substellar companions. The thermal evolution of a substellar companion depends on the properties of its atmosphere (clouds, molecular opacities) and internal structure. The left panel of Fig. 1 shows that for given luminosity and age, the corresponding mass of a giant planet can vary significantly depending on the model used for the physics of the accretion. The right panel of Fig. 1 shows that the mass of a planet core strongly affects the mass-luminosity-age relation, with planets with more massive cores being brighter for a given age. Finally, Figure 2 illustrates the influence of the atmospheric model on the mass-luminosity-age relations.

2.2 Synergies with SPHERE+ and GRAVITY+

Strong synergies for exoplanet imaging exist between the ELT and the instruments SPHERE+ and GRAVITY+ planned in the VLT2030 roadmap (Boccaletti et al. 2020; Eisenhauer 2019, see also Paumard et al., this volume). SPHERE+ is an upgrade project for SPHERE to improve its high-contrast performance toward smaller angular separations to access closer physical separations to the stars. It will also improve the performance toward fainter stars to search for young giant protoplanets in a larger sample of the protoplanetary disks imaged with ALMA. SPHERE+ will be more suited than the ELT to complete large surveys and first characterizations of young

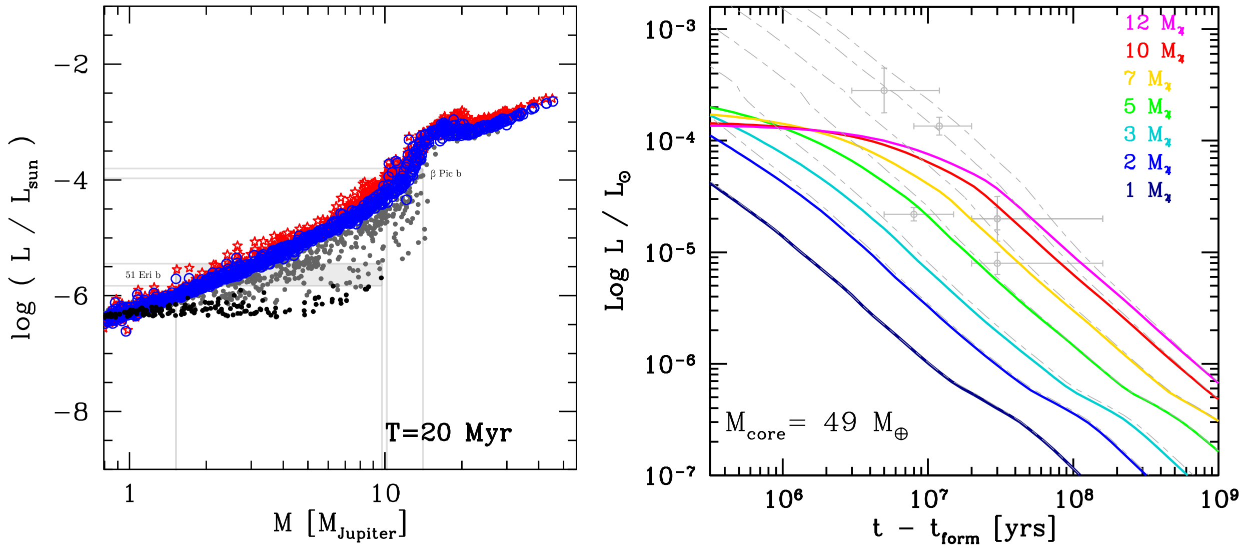

Fig. 1. Left: Bolometric luminosity of giant planets as a function of their mass for an age of 20 Myr for several accretion models differing by the efficiency of the accretion shock of the planetesimals onto the planetary core (from red: hot accretion to gray and black: cold accretion). Two known directly-imaged giant exoplanets are also shown (gray lines). Figure from Mordasini et al. (2017). **Right:** Bolometric luminosity of giant planets as a function of time after formation for several total planet masses (colors), a given core planet mass of 49 Earth masses, and a cold accretion model. The dotted-dashed curves show the predictions for a hot accretion model. Known directly-imaged planetary-mass companions are also shown (data points with error bars). Figure from Mordasini (2013).

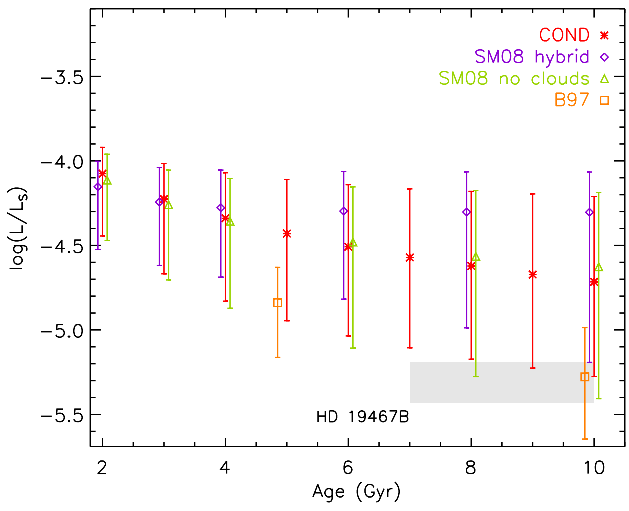

Fig. 2. Bolometric luminosity as a function of the age of the brown dwarf HD 19467B (gray area) compared to evolutionary tracks from the models COND (Baraffe et al. 2003), Saumon & Marley (2008) (for two cloud models, a cloudless model and a hybrid model designed to reproduce the L/T transition), and Burrows et al. (1997) using the companion mass measured from an RV-imaging-astrometry orbital fit and the theoretical hydrogen-burning mass limit (data points). Small horizontal offsets are applied to all models except for COND for clarity. Figure from Maire et al. (2020).

massive giant exoplanets at separations down to the snow line (∼3 au). These planets will be ideal targets for a follow-up with the ELT to characterize their atmospheric and orbital properties more finely at higher spectral resolutions and astrometric precisions, respectively.

GRAVITY+ is an upgrade project for GRAVITY to extend its capabilities toward fainter science targets and achieve milliarcsecond astrometry over the entire sky. GRAVITY+ will be more suited than the ELT for a fine orbital characterization of known companions in particular mature giant exoplanets detected in RV surveys or with Gaia. GRAVITY has already allowed for the first imaging confirmation of an exoplanet discovered with RV, the giant exoplanet β Pictoris c (Nowak et al. 2020), which orbits the young star β Pictoris ($\sim$24 Myr). The orbit of β Pictoris c is inner to the orbit of the giant exoplanet β Pictoris b which was previously discovered with high-contrast imaging. GRAVITY requires a precise knowledge of the position of the planets because of the limited field of view of its dual-fiber mode (60 mas). However, RV cannot constrain the orientation of the orbital plane. The detection of β Pictoris c was possible by assuming that its orbit is coplanar with the orbit of β Pictoris b. To detect with GRAVITY+ other RV-detected exoplanets (which are found in mature systems), it will be critical to constrain their position in the field of view beforehand. This could be done with coronagraphic imaging, with SPHERE+ or MICADO, HARMONI, or METIS on the ELT. Alternatively, if the star shows an astrometric signature with Gaia, orbital predictions from joint fits of RV and Gaia data could be used.

3 Monitoring of the motion of substructures in circumstellar disks

Another major science case that will benefit from the improved astrometric precision of the ELT in high-contrast imaging is the monitoring of the slow motion of substructures (e.g., spirals, rings, shadows) in circumstellar disks to constrain the underlying production mechanism. For instance, spiral arms could be produced by a gravitational instability in the disk or by the gravitational interactions of a giant planet embedded in the disk. These scenarios predict different rotation speeds for the spiral arms. The rotational speed of the spiral arms of MWC 758 was measured using SPHERE images taken 4 years apart from each other and was shown to be compatible with a planet-driven scenario (Ren et al. 2020). Thanks to the ELT, monitoring of disk features will be feasible at higher spatial resolutions and precisions and for a larger sample of young protoplanetary disks in star-forming regions and fainter or less massive debris disks.

4 Conclusions

Thanks to its high angular resolution and sensitivity, the ELT will bridge the gap between the high-contrast imaging, RV, and/or astrometric techniques for the characterization of exoplanets beyond 1 au from the stars. The combination of these techniques is essential to break the degeneracies between the mass, luminosity, and age of the planets and to perform strong tests of the models of formation, evolution, atmosphere, and internal structure of exoplanets. The ELT will also be complementary to the VLT2030 instruments SPHERE+ for detailed follow-up characterization of newly-discovered young massive giant exoplanets and GRAVITY+ for first imaging snapshots of RV or Gaia exoplanets to constrain or refine the on-sky position for finer astrometric characterization.

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