Imaging polarimetry for the characterisation of exoplanets and protoplanetary discs : scientific and technical challenges

Juan Ovelar, M. de

Citation

Juan Ovelar, M. de. (2013, December 12). *Imaging polarimetry for the characterisation of exoplanets and protoplanetary discs : scientific and technical challenges*. Retrieved from https://hdl.handle.net/1887/22837

Author: Juan Ovelar, Maria de
Title: Imaging polarimetry for the characterisation of exoplanets and protoplanetary discs : scientific and technical challenges
Issue Date: 2013-12-12

English Summary

Imaging exoplanets and protoplanetary discs

The field of exoplanets is a relatively young and extremely exciting one in Astronomy. Up to this date, more than 700 exoplanets have been discovered and there are more than 3000 candidates waiting to be confirmed. The reason why we have *"candidate"* exoplanets is that some of the most successful techniques we use to detect exoplanets are *"indirect"*, meaning that they provide information with which we can infer the presence of a planet rather than directly detect it. Figure A shows the confirmed exoplanets known up to date with those detected through direct imaging marked as red diamonds, those detected through indirect methods marked as blue dots and the planets in our Solar System marked in yellow squares. This figure illustrates the fact that it is considerably more difficult to get an image of an exoplanet than to infer its presence form indirect information.

The trouble with directly detecting exoplanets comes mainly from two facts. First the difference in brightness between the star and the planet is large (about 9 orders of magnitude for a planet like Jupiter and a star like the Sun, and up to 11 for a planet like our Earth), which makes it extremely difficult to distinguish the light of the planet from the halo of the central star-light. Second, the optical elements of the telescopes we use to get images spread the light from the star (and the planet) into a diffraction pattern that limits our capability to look close in to the central star[1]. On top of these limitations, when we observe stars from ground-based telescopes, the light from the stars and the planets that orbit them has to go through the atmosphere which is not stationary. This causes the light pattern to look different as time goes on (this is the reason why stars *twinkle* in the sky when we look at them from the ground) and the final images of the stars to look blurry, which complicates the task of distinguishing the small and faint planet from its parent star.

To overcome these problems, astronomers and engineers have developed quite successful observing and data reduction techniques, but even with their help, the range of planet masses and separations from the star that are detectable through direct imaging methods are far from allowing the detection of a planet like the Earth (note that the red diamonds in Figure A

---

[1] This limit is known as the "diffraction limit" of the telescope and depends on the wavelength of observation and the diameter of the primary mirror of the telescope, such that, for the same wavelength, one can see things closer to the star when using bigger mirrors

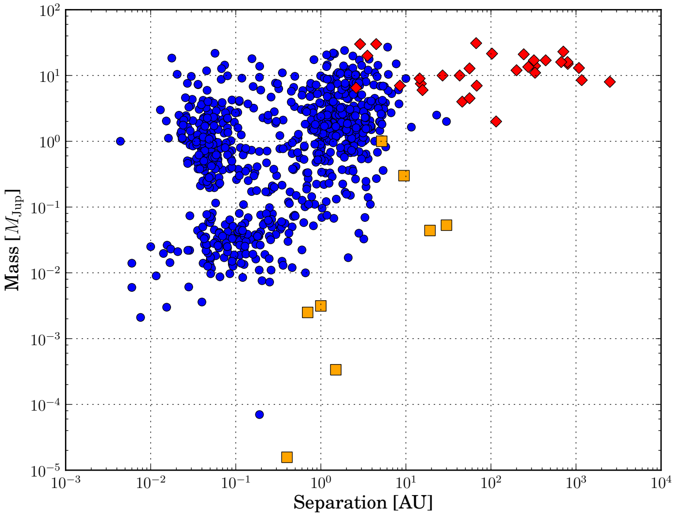

Figure A: Mass vs. separation plot of currently confirmed exoplanets. The red diamonds are the ones that have been detected by direct imaging and the yellow squares are the planets in our Solar System. *Source:* exoplanet.eu.

correspond to planets that are more massive than Jupiter and orbit the star relatively far away from their parent star). To put Figure A into perspective consider that our most massive planet, Jupiter, will be placed at coordinates (5 AU, 1 $M_{\rm Jup}$), where AU stands for astronomical units (one astronomical unit corresponds to the distance between the Sun and the Earth). The outermost planet in our Solar System, Neptune, will occupy point (30 AU, 0.05 $M_{\rm Jup}$), while the Earth would stand at position (1 AU, 0.003 $M_{\rm Jup}$). It is therefore clear that we need to improve our imaging capabilities if we aim to detect planets similar to the ones that form our Solar System.

The reason why detecting planets directly is so important is because we can perform much better characterisation. Of course our curiosity as human beings is not content with just knowing an exoplanet is there; we want to know what the exoplanet looks like, if it features oceans and continents like the Earth, if it looks more like the dry surface of Mars or if its climate is governed by strong storms as it is the case of, for example, Jupiter. We want to know if life as we know it can be hosted by that planet, if there is vegetation, water, or if the atmosphere is filled with sulfur instead of nitrogen and oxygen. All these questions can be much better addressed if we can directly register the light coming from the planet, which contains information about its composition and structure. As an example of directly imaged exoplanets where characterisation has been performed on, Figure B shows two images of the

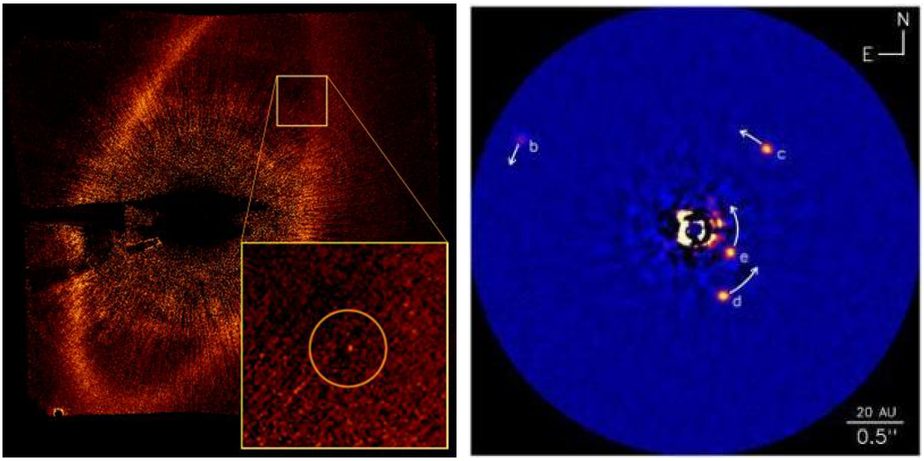

Figure B: Images of two directly detected exoplanets. *Left:* Fomalhaut b (Kalas et al. 2008). *Right:* HR8799 b,c,d and e (Marois et al. 2008, Marois et al. 2010). *Images credit*: (from left to right) Paul Kalas/UC Berkeley, NASA, ESA; NRC-HIA, C. Marois, and Keck Observatory

exoplanets orbiting around the stars known as Fomalhaut and HR 8799.

Another important field where direct imaging becomes crucial is that of protoplanetary discs, which are the cradles of planets. Planet formation is a natural outcome of star formation itself. A star forms out of a cloud of gas and dust that collapses under its own gravitational potential. But not all the gas and dust present in the original cloud ends up in the star. The remaining matter ends up forming a rotating circumstellar disc that keeps on feeding the star with material and also, we believe, undergoes planet formation processes which can create gaps and holes in the disc. Figure C shows an illustration of this process. The exact process by which planets form is not completely understood, and it is most likely not unique since the characteristics of the exoplanets we know are very different from one another. It is therefore extremely important to investigate the evolution of these protoplanetary discs in which planet formation takes place. Imaging these discs at visible and near-infrared wavelengths and, in particular, the closest regions to the star, poses similar challenges as exoplanet imaging, since the material surrounding the star is also very faint.

Polarimetry to improve our understanding of planets and protoplanetary discs

An important technique that can be used to improve our imaging and characterisation capabilities of circumstellar environments is polarimetry. Light is composed of electric and magnetic waves that vibrate in directions perpendicular to each other as the light propagates.

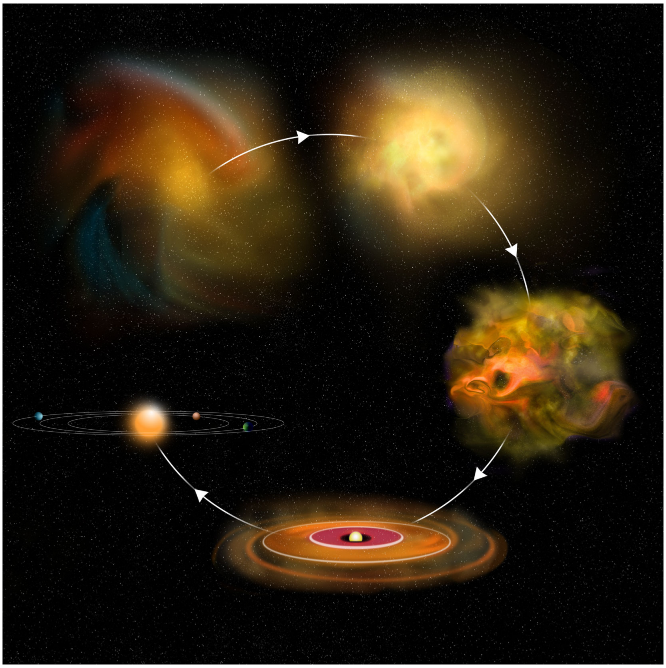

Figure C: Illustration of the star (and planet) formation process. *Image credit:* Bill Saxton, NRAO/AUI/NSF

If the components of the electric field propagate maintaining a fixed difference in phase and amplitude we say that light is polarised. Depending on the particular values of these differences light can be linearly, circularly and elliptically polarised. Light coming from the stars is mainly unpolarised because it is composed of multiple waves, each one polarised in a different way. The net result is that the electric field does not feature fixed ratios of phase and/or amplitude and therefore the light has no preferential polarisation state. However, processes such as reflection and scattering can polarise light that is originally unpolarised and this is the effect astronomical polarimetry exploits. When the light of a star reaches the atmosphere of a planet or the material in a protoplanetary disc a fraction of it gets scattered by the small particles that compose the medium. These scattered radiation becomes linearly polarised in the scattering process which makes it possible to distinguish it from the light of the central star, reducing the difference in brightness between the star and the surrounding matter by up to 6 orders of magnitude (level achieved with current techniques and instruments). Figure D illustrates this idea.

In addition to helping overcome the contrast problem, the resulting polarisation state of the scattered light depends strongly on characteristics of the particles that scatter the radiation

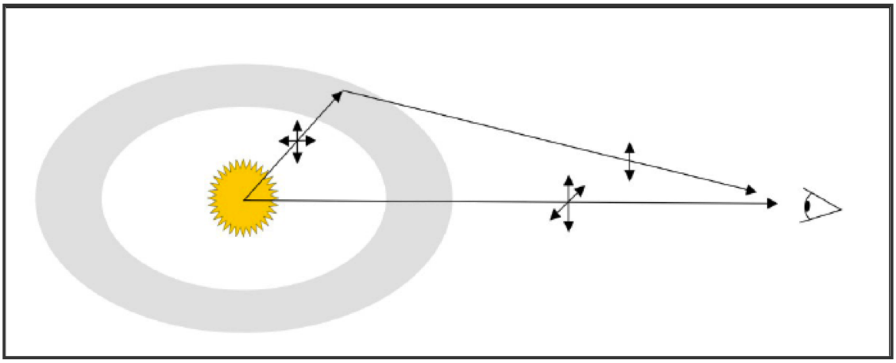

Figure D: Schematic view of the linear polarisation of light that results from the scattering of star-light on the dust particles present in a circumstellar disc. *Image credit:* M. Rodenhuis

such as, for example, size, composition, and shape. Therefore the analysis of the polarised signal coming from the circumstellar matter can yield information that is not obtainable by other means. This thesis is dedicated to explore the ways in which polarimetry can help us to understand exoplanets and their formation, and to develop new techniques to overcome the scientific and technical challenges its use poses.

In Part I of this thesis, we present several studies that aim to contribute to the improvement of characterization of planets and the environment in which they form through direct imaging and polarimetry. In Chapter 2, we present the first attempt to obtain polarisation signal from the exoplanets orbiting HR 8799 (right image in Figure A). This exciting study, which is not yet finished, is based on combining current state-of-the-art polarimetric, observing and data reduction techniques to measure the polarised signal of these massive planets which contains very important information about the structure of their atmosphere and some physical parameters such as the orientation of their spin axis and the amount of flattening their rotation around this axis causes to the globe. So far, we have not been able to detect the signal, but our results show promising avenues for the application of this combination of techniques and we still hope to improve the current results upon further investigation.

In Chapter 3 we perform a study in which we combine observations at different wavelengths and with different observing techniques to constraint properties of a planet that creates a gap/hole in a disc as it forms. These type of disc, featuring holes and/or gaps are known as *transition discs* because they are believed to be the transition phase between a full disc and a discless star possibly orbited by a planetary system. Although other theories have been proposed to explain the gaps/holes, it is possible to create these features by forming planets in the disc, and we show that, if this is the case, the characteristics of the structure we see in the disc using different observing techniques can help us constraining characteristics of the planet without directly seeing it. In particular, the combination of imaging polarimetry at visible wavelengths and interferometric observations at sub-mm wavelengths can quite tightly constrain the planet's mass and separation.

The study presented in Chapter 4 is the only study in this thesis that does not (directly) include the use of polarimetry. The reason for this is that it is a statistical study on the population of protoplanetary discs of which the size (i.e. the radius) has been already measured through direct imaging[2]. These discs are sometimes orbiting stars that are surrounded by others. Indeed, most stars form in groups of stars of which some will remain close to each other for a long time affecting the evolution of one another. It is therefore interesting to ask oneself the question wether the environment in which a star evolves has any impact on its potential to form planets, since a protoplanetary disc can be perturbed by interactions with surrounding stars. This is precisely the goal of the study. Unfortunately, we do not have images of discs in regions very populated by stars, but the region of highest density of stars in which discs have been imaged (the Orion Nebula Cluster) seems to feature smaller discs, suggesting that the environment does have a truncation effect. To finally prove this relation between the environment and the disc properties we need to explore regions of higher density of stars for what we propose to perform new observations with the brand new Atacama Large Millimetre/sub-millimetre Array (ALMA).

An important limitation for performing polarimetric imaging is the amount of photons a telescope is able to collect. These light collecting capabilities are mainly determined by the diameter of the telescope's primary mirror. The largest telescopes currently operational have primary mirror diameters of about 8-10 metres. Fortunately, in the next decade astronomers will be able to start observing with telescopes much bigger than these and the amount of light we can collect from faint objects like exoplanets and protoplanetary discs will increase greatly, as well as the resolution with which we will be able to observe. One of these upcoming facilities is the European Southern Observatory's (ESO's) European Extremely Large Telescope (E-ELT) which will have a primary mirror of 39 metres in diameter. The construction and operation of such telescope is an extremely challenging task due to the complexity of the systems that are needed to control the positioning and good functioning of all optical elements, which will feature sizes never considered before.

The second part of this thesis (Part II) is oriented to study the instrumental effects generated by the different optical elements of the E-ELT telescope. As we have mentioned before, the polarisation state of light gets affected by processes like reflection and scattering. This is an advantage for imaging exoplanets and circumstellar discs, but it also is a disadvantage since the main elements of a telescope are mirrors. Every reflection on a mirror creates polarisation, and also modifies the polarisation that light already had, making difficult to disentangle what polarised signal came from the astronomical object and what was created by the telescope. For this reason, it is very important to make a thorough study of the telescope, characterise these effects and come up with techniques to correct for them. And this is precisely what we do in Chapters 5 to 7, finding that, although the polarimetric effects in this complex telescope are large, it is possible to correct them and sometimes completely cancel them, assuring the conditions to perform very sensitive and accurate polarimetry.

---

[2] Some of the disc radii used in the study have been measured, for the first time or confirmed, using polarimetric imaging.