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CoRoT pictures transiting exoplanets

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ABSTRACT

The detection and characterization of exoplanets have made huge progresses since the first discoveries in the late 1990s. In particular, the independent measurement of the mass and radius of planets, by combining the transit and radial-velocity techniques, allowed exploring their density and hence, their internal structure. With CoRoT (2007–2012), the pioneering CNES space-based mission in this investigation, about thirty new planets were characterized. CoRoT has enhanced the diversity of giant exoplanets and discovered the first telluric exoplanet. Following CoRoT, the NASA Kepler mission has extended our knowledge to small size planets, multiple systems and planets orbiting binaries. Exploring these new worlds will continue with the NASA/TESS (2017) and ESA/PLATO (2024) missions.

1. Introduction

The search for exoplanets around solar-type stars has started in the 1990s with the direct imaging method and the radial-velocity method. While the first one uses high-contrast and high-resolution imaging of nearby stars to search for the dim light of a sub-stellar companion, the second method uses indirect measurements of stars and searches for velocity wobbling due to the gravitational pull by an invisible planet. Both methods had their first results in 1995: the first detected brown dwarf companion Gl 229 B (about 50 Jupiter masses) by direct imaging (Oppenheimer et al., 1995) and the first detected Jupiter-like exoplanet 51 Pegasi b, orbiting a solar-type star (Mayor and Queloz, 1995). The main difference between these two companions is probably their distance to their parent star: while the orbital period of Gl 229 B is larger than 10,000 years, the one of 51 Pegasi b is 4.5 days. This exemplifies the different biases of the two methods, imaging being sensitive to planets at long orbital period, whereas radial-velocity is performant for systems at short orbital period. In the meantime, the Hubble Space Telescope was discovering that young protostars were being formed in opaque, dusty disk structures, another hint that planetary formation could be a universal phenomenon.

These discoveries triggered a new field of research and extreme enthusiasm in the astrophysical community. A third method is quickly proposed and experimented on the first detected radial-velocity planets: it consists in searching for a slight dimming of the star's light that would be due to the crossing of a planet on the stellar disk – a transit. This method works for planets whose orbit is perfectly aligned with the line of sight between the observer and the parent star. To discover transiting planets, it is thus necessary to observe for a long time a very large number of stars. The method is, as the radial-velocity method, biased towards detecting short period planets.

A few months after the discovery of 51 Peg b, a team of French astronomers and CNES engineers proposed the

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spaced-based CoRoT mission (Baglin, 2003), aimed at observing large numbers of stars with extreme photometric precision and long time series – as only possible from space – in search for exoplanet transits. While CoRoT was designed, built, and integrated, a few exoplanetary transits were being detected from ground-based observatories. The first of them is HD 209458 b (Charbonneau et al., 2000), a short period Jupiter-like planet as 51 Pegasi b. The independent detections of HD 209458 b with the radial-velocity and the transit methods have been a strong confirmation that these giant planets very close to their stars actually existed. The combination of both methods also allowed us to measure the planet's mass (from the radial-velocity amplitude) and its radius (from the transit depth), hence the bulk density of the planet. While the density of HD 209458 b is within the range of the Solar System's largest gaseous planets, the planet radius could not be reproduced by models of internal structure: the giant exoplanet appeared largely inflated, for its star's composition and age. When CoRoT was then launched in 2006, there were 15 known transiting exoplanets; all were giant, gaseous planets, whose transits (1–3% deep, 2–3 hour long) were easily detected from ground-based telescopes of small size (typically less than 1 m).

In this article, we will review the findings of the CoRoT mission in its search for exoplanets. After describing the mission concept and instrument, we will review the process that starts with candidates and leads to exoplanets. Finally, we will emphasize the learning from the CoRoT exoplanets and have a look towards other exoplanets' surveys and future missions in this field.

2. The CoRoT satellite

Searching for exoplanets with the transit method requires both very good photometric precision and a very large number of observed stars. The duration of the observing run sets the domain of orbital periods that is within reach, as the transit occurs once per orbital period (note that the secondary transit, occurring when the planet passes behind the star with respect to the observer, is only rarely detected due to a much smaller amplitude and additional constraint on the geometry). In addition to transit detection, precise stellar photometry from space also allows us to probe the stellar interiors with asteroseismology, another main science objective of CoRoT (on a smaller number of much brighter stars) (Baglin, 2003). In the domain of transiting exoplanets, a space-based mission allows one to detect transiting planets of smaller size and/or of longer orbital period than ground-based photometric surveys.

The CoRoT design can be summarized by Auvergne et al., 2009:

- a PROTEUS platform ensuring a polar orbit at 900 km of altitude and a 6-month continuous access to a given field of view;
- a 27-cm mirror in an off-axis telescope;
- a focal plane divided in two, with an asteroseismology channel and an exoplanet channel; a field of view of $1.4^\circ \times 2.8^\circ$ for the exoplanet channel and 2.3 arcsec pixel size;
- an operation plan adapted to the satellite orbit, with a succession of short (15–30 days) and long runs (80 or 150 days);
- two main fields of observation, located in two opposite regions in the Milky Way towards the Monoceros and Aquila constellations and close to the Galactic plane. These locations were optimized for stellar density, considering other observing constraints, such as the presence of bright nearby stars of scientific interest for the asteroseismology channel;
- a $7{\cdot}10^{-4}$ photometric precision on a $R = 15$ star in a 2-h timescale;
- about 6000 stars observed simultaneously in the exoplanet channel, in the magnitude range of $V = 11$ to 16.5;
- 32-s and 8-min temporal samplings on the light curves calculated onboard, and a duty cycle of 91%;
- for the 30% brightest stars, three-color light curves generated by a low-resolution prism. Only the white light curve is provided for all other stars.

Launched on 26 December 2006 by a Soyouz rocket from Baikonour, the CoRoT satellite has provided astronomical data from February 2007 (after a run of commissioning) to November 2012. Its lifetime was originally granted to be three years, and was extended twice. Observations were discontinued due to electronic failures, probably due to high-energy particle bombardment. The satellite was stopped in June 2014 after programming its slow decay to Earth.

A picture of the satellite during its integration in Cannes is shown in Fig. 1. An archive of the CoRoT data is now fully public and can be accessed at http://idoc-corotn2-public.ias.u-psud.fr.

3. Candidates or planets?

In total, 163,664 stars were observed during the lifetime of CoRoT for a total of 169,967 light curves. Light curves were processed onboard and sent to Earth where additional data reduction got rid of instrumental effects. Several algorithms for transit detection were then applied to the light curves, generating several lists of exoplanet candidates.

A planet candidate is not necessary a planet. There are several other astrophysical scenarios that mimic the planetary transits, involving multiple eclipsing stars rather than planets: grazing binaries, giant–dwarf binaries, eclipsing binary diluted by a third body. If the detected transit is very shallow, a possible contamination is a giant transiting planet orbiting a star diluted by another star. In such a case, the planet interpretation is correct, but the inferred radius of the planet would be largely incorrect.

As CoRoT provides lists of transiting candidates, these are then submitted to series of tests to evaluate their origin. For instance, the three-colored light curves, when available, can be used to eliminate candidates showing different transit depths in the different colors (signature of a blended stellar scenario). The distance between transits