TRAPPIST: TRAnsiting Planets and PlanetesImals Small Telescope

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TRAPPIST is a 60-cm robotic telescope that was installed in April 2010 at the ESO La Silla Observatory. The project is led by the Astrophysics and Image Processing group (AIP) at the Department of Astrophysics, Geophysics and Oceanography (AGO) of the University of Liège, in close collaboration with the Geneva Observatory, and has been funded by the Belgian Fund for Scientific Research (F.R.S.-FNRS) and the Swiss National Science Foundation (SNF). It is devoted to the detection and characterisation of exoplanets and to the study of comets and other small bodies in the Solar System. We describe here the goals of the project and the hardware and present some results obtained during the first six months of operation.

The science case

The hundreds of exoplanets known today allow us to place our own Solar System in the broad context of our own Galaxy. In particular, the subset of known exoplanets that transit their parent stars are key objects for our understanding of the formation, evolution and properties of planetary systems. The objects of the Solar System are, and will remain, exquisite guides for helping us understand the mechanisms of planetary formation and evolution. Comets, in particular, are most probably remnants of the initial population of planetesimals of the outer part of the protoplanetary disc. Therefore the study of their physical and chemical properties allows the conditions that prevailed during the formation of the four giant planets to be probed.


E. Jehin/ESO

Figure 1. The TRAPPIST telescope in its 5-metre enclosure at the La Silla Observatory, Chile.

TRAPPIST is an original project using a single telescope that has been built and optimised to allow the study of those two aspects of the growing field of astrobiology. It provides high quality photometric data of exoplanet transits and allows the gaseous emissions of bright comets to be monitored regularly. The project is centred on three main goals: (1) the detection of the transits of new exoplanets; (2) the characterisation of known transiting planets, in particular the precise determination of their size; and (3) the survey of the chemical composition of bright comets and the evolution of their activity during their orbit.

A dedicated robotic telescope

The basic project concept is a robotic telescope fully dedicated to high precision exoplanet and comet time-series photometry, providing the large amount of observing time requested for those research projects. Exoplanet transits typically last several hours, up to a full night. There are now many known transiting planets, and many more candidates found by transit surveys which need to be confirmed and characterised. Moreover these targets need to be observed at very specific times, during eclipses, putting even more constraints on telescope availability. Similarly a lot of observing time is obviously needed to monitor the activity of several comets with a frequency of a few times per week. Some comets are known, but others appear serendipitously. For the latter, telescope availability is crucial if we want to react rapidly to observe those targets at the appropriate moment and for several hours or nights in a row; this strategy can provide unique datasets impossible to obtain otherwise.

Telescope and instrumentation

For low cost operations and high flexibility, TRAPPIST (see Figure 1) had to be a robotic observatory. The observation programme, including the calibration plan, is prepared in advance and submitted daily to a specific software installed on the computer controlling the observatory. This computer controls all the technical aspects of the observations: dome control, pointing, focusing, image acquisition, astrometry and software guiding, calibrations, data storage... It is in sleep mode during daytime and wakes up one hour before sunset, opening the dome and starting to cool the CCD. This process is made possible thanks to a collection of computer programs working together and interacting with the telescope, dome, CCD camera, filter wheels and meteorological station. Such a complete and rapid integration, using mostly off-the-shelf solutions, would have been impossible a few years ago and

Figure 2. Close-up of the 60-cm TRAPPIST telescope.

allowed us to set up the experiment in less than two years.

The observatory is controlled through a VPN (Virtual Private Network) connection between La Silla and Liège University. The telescope and each individual subsystem can be used from anywhere in the world, provided an internet connection is available. In case of a low-level mechanical failure, we can count on the help of the Swiss technician on site or the La Silla staff.

Hundreds of images, amounting to 2–15 GB, are produced every night. Reduction pipelines run on a dedicated computer installed in the control room. For the exoplanet programme, only tables and plots with the final results are transferred to Liège, while for the comet programme, it is often necessary to transfer dozens of frames in order to perform more interactive tasks on the images. Every third month, a backup disk is sent to Belgium and transferred to the archive machine.

The telescope is a 60-cm f/8 Ritchey–Chrétien design built by the German ASTELCO company (see Figure 2). Owing to its open design with carbon fibre and aluminium components, it weighs only 65 kg and was allied to a compact German equatorial mount, the New Technology Mount NTM-500, from the same company. This robust mount uses direct drive technology to avoid the well-known periodic errors found on the usual equatorial mounts for small telescopes and therefore permits accurate pointing and tracking. The accuracy of the tracking allows an exposure time of four minutes maximum, which is usually enough for our bright targets. Each frame is calibrated in right ascension and declination and software guiding runs continuously to keep the target centred on the same few pixels for the whole exposure sequence.

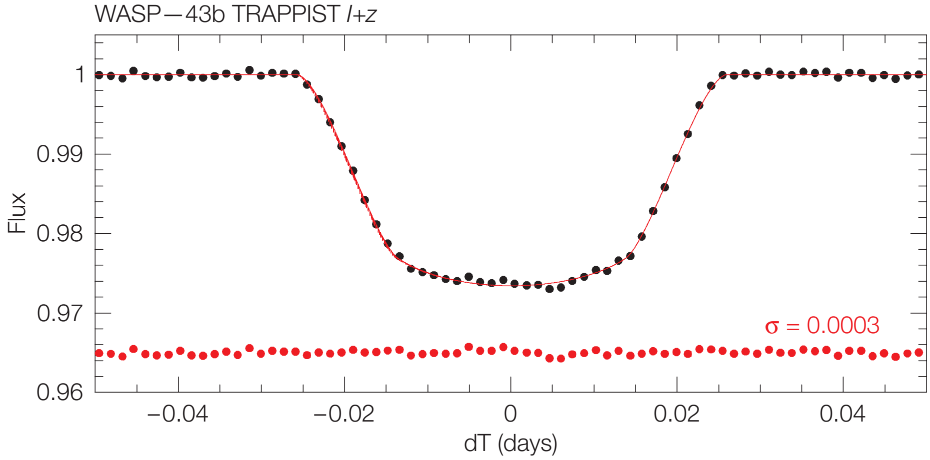

Figure 3. TRAPPIST *I* + *z* transit photometry of the planet WASP-43b, period-folded and binned per two minute intervals, with the best-fit transit model superimposed. The residuals of the fit, shifted along the *y*-axis for the sake of clarity, are shown below and their standard deviation is 300 parts per million (ppm). This light curve results from the global analysis of 20 transits observed by TRAPPIST for this exoplanet.

The CCD camera was built by Finger Lakes Instrumentation, with thermoelectric cooling and a CCD of the latest generation. This is a thinned broadband backside-illuminated Fairchild chip with 2048 × 2048 15-µm pixels providing a field of view of 22 by 22 arcminutes and a plate scale of 0.6 arcseconds per pixel. The sensitivity is excellent over all the spectral range, with a peak of 98 % at 750 nm, declining to around 80 % at 550 nm and 60 % at 300 nm. It is optimised for low fringe level in the far red and achieves a sensitivity of 40 % at 950 nm. The gain is set to 1.1 e^-/ADU. There are three different readout modes: a low noise readout mode (readout noise [RON] 9.7 e^- in 8s), a fast mode (RON 14 e^- in 4s) and a very fast readout of 2s using two quadrants. The cooling is –55 deg below ambient, usual operation being at –35 °C with a dark count of 0.11 e^-/s/pixel. Typical magnitudes reached in 20s with a 2 × 2 binning (1.3 arcseconds per pixel) and a 10 % accuracy are *B*-band 16.2, *V*-band 16.4, *Rc*-band 16.4, *Ic*-band 15.5 and *I* + *z*-band 15.6; and in 200 seconds, *B*-band 19.7, *V*-band 19.4, *Rc*-band 19.2 and *Ic*-band 18.1.

The camera is fitted with a double filter wheel specifically designed for the project and allowing a total of 12 different 5 × 5 cm filters and one clear position. One filter wheel is loaded with six broadband filters (Johnson-Cousins BVRcIc, Sloan *z*′, and a special *I* + *z* filter for exoplanet transits) and the other filter wheel is loaded with six narrowband filters for the comet programme. The comet filters were designed by NASA for the international Hale–Bopp campaign (Farnham et al., 2000). Four filters isolating the main molecular emission lines present in cometary spectra (OH [310 nm], CN [385 nm], C_3 [405 nm], C_2 + NH_2 [515 nm]) are permanently mounted, while the two other filters of the set (CO^+ [427 nm] and H_2O^+ [705 nm]) are also available. In addition two narrowband filters, isolating “continuum windows” (BC [445 nm] and GC [525 nm]) for the estimation of the solar spectrum reflected by the dust of the comet, are mounted.

Installation, first light and start of operations

The telescope was installed in April 2010 in the T70 Swiss telescope building belonging to Geneva University (Figure 1). This facility had not been used since the 1990s and was completely refurbished in early 2010. The old 5-metre dome (AshDome) was equipped with new azimuth motors and computer control. A Boltwood II meteorological station with a cloud sensor and an independent rain sensor was installed on the roof to record the weather conditions in real time. In case of bad conditions (clouds, strong wind, risk of condensation, rain or snow), the dome is automatically closed and the observations interrupted to guarantee the integrity of the telescope and equipment. An uninterruptable power supply (UPS) keeps the observatory running for 45 minutes during an electrical power cut and an emergency shutdown is triggered at the end of this period. Several webcams inside and outside the building help us to check what is going on in the observatory if needed. After two months of commissioning on site, TRAPPIST "first light" took place remotely on 8 June 2010, together with a press conference at Liège University[1]. Technical tests, fine tuning of the software as well as the first scientific observations were performed in remote control mode until November 2010. The fully robotic operation then started smoothly in December with several months of superb weather until the start of the winter.

The two scientific aspects of this dedicated telescope and the first results are described below.

Survey of transiting exoplanets

The transit method used by TRAPPIST is an indirect technique, based on the measurement of the apparent brightness of a star. If a planet passes in front of the star, there is a slight observable decline in the apparent luminosity, as the planet eclipses a small fraction of the stellar disc. Recording this periodic event allows the radius of the planet to be measured. Combined with the radial velocity method, the transit method provides the mass and density of the planet, allowing us to constrain its bulk composition. Furthermore, the special geometry of the orbit makes the study of important properties of the planet (e.g., atmospheric composition, orbital obliquity, etc) possible without the challenge of having to spatially resolve it from its host star. Transiting planets are thus key objects for our understanding of the vast planetary population hosted by the Galaxy.

Discovery of more transiting planets is important to assess the diversity of planetary systems, to constrain their formation and the dependence of planetary properties on external conditions (orbit, host star, other planets, etc.). TRAPPIST is participating in this effort through several different projects.

Detection of new transiting planets

On account of its extended temporal availability and high photometric precision, TRAPPIST has very quickly become an important element for the transit surveys WASP[2] and CoRoT[3]. It is used to confirm the candidate transits detected by these surveys and to observe them with better time resolution and precision to discriminate eclipsing binaries from planetary transits. TRAPPIST observations have so far rejected more than 30 WASP candidates as being eclipsing binaries. It has confirmed, and thus co-discovered, ten new transiting planets (e.g., Triaud et al., 2011; Csizmadia et al., 2011; Gillon et al., 2011).

The search for transits of the planets detected by the radial velocity (RV) technique is another important science driver for TRAPPIST. RV surveys monitor stars significantly brighter than the transit surveys. The few RV planets that were revealed afterwards to be transiting, have brought improved knowledge of exoplanet properties because a thorough characterisation is possible (e.g., Deming & Seager, 2009). These planets thus play a major role in exoplanetology. In this context, TRAPPIST is used to search for the possible transits of the planets detected by the HARPS (Mayor et al., 2003) and CORALIE (Queloz et al., 2000) Doppler surveys. For the late M-dwarfs observed by HARPS, TRAPPIST is even able to detect the transit of a massive rocky planet.

Characterisation of known transiting planets

Once a transiting planet is detected, it is of course desirable to characterise it thoroughly with high precision follow-up measurements. Assuming a sufficient precision, a transit light curve allows a number of parameters to be thoroughly constrained: (i) the planet-to-star radius ratio; (ii) the orbital inclination; (iii) the stellar limb-darkening coefficients; and (iv) the stellar density (assuming the orbital period is known). This last quantity can be used with other measured stellar quantities to deduce, via stellar modelling, the mass of the star, which leads finally to the stellar and planet radii (Gillon et al., 2007; 2009). So far, we have gathered many high precision light curves for two dozen transiting planets. These data will not only allow us to improve our knowledge of these planets (size, structure), but also to search for transit timing variations that could reveal the presence of other planets in the system. Since TRAPPIST is dedicated to this research project, it can monitor dozens of transits of the same planet, leading to an exquisite global precision, as shown in Figure 3.

Transit search around ultra-cool dwarf stars (UCDs)

We have selected a sample of ten relatively bright late-M stars and brown dwarfs. For each of them, we have started an intense monitoring campaign (several full nights) to search for the transits of the ultra-short period (less than one day) terrestrial planets that are expected by some planetary formation theories. The photometric variability of these UCDs brings a lot of information on their atmospheric and magnetic properties, and the by product of this TRAPPIST project will thus be a significant contribution to the understanding of these fascinating UCDs that dominate the Galactic stellar population.

Survey of the chemical composition of comets

TRAPPIST is the only telescope in the southern hemisphere equipped with the instrumentation to detect gaseous comet emissions on a daily basis. As recently outlined during a NASA work-

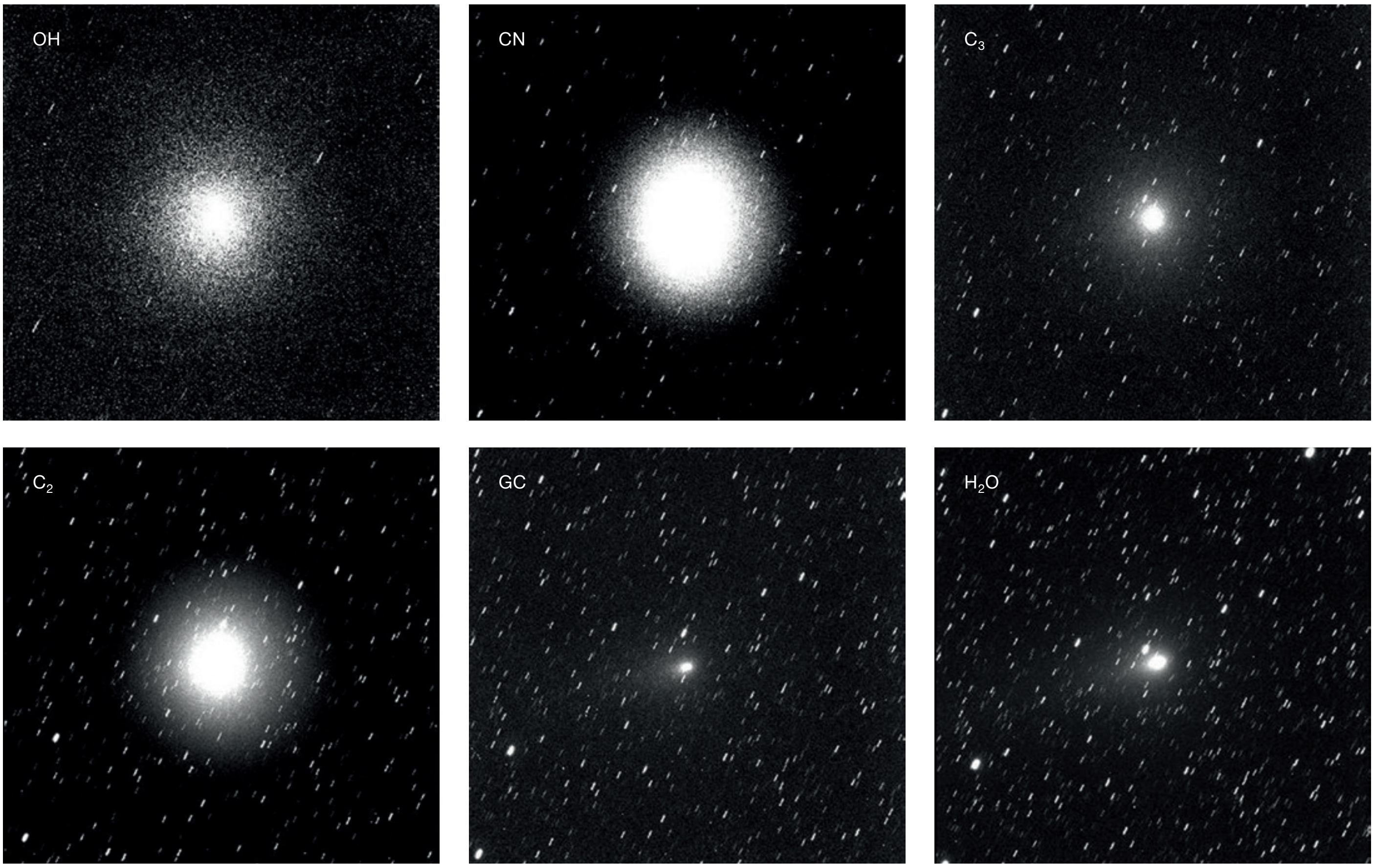

Figure 4. Comet 103P/Hartley 2 imaged with TRAPPIST through the different cometary filters on 5 November 2010: OH, CN, C_3, C_2, green continuum (GC) and H_2O^+. Note the different shapes and intensities of the cometary coma in each filter.

shop[4], the huge amount of data collected by TRAPPIST will bring crucial new information on comets and will rapidly increase statistics, allowing comets to be classified on the basis of their chemical composition. Linking those chemical classes to dynamical types (for instance short period comets of the Jupiter family and new long period comets from the Oort Cloud) is a fundamental step in understanding the formation of comets and the Solar System.

For relatively bright comets ($V \leq 12$ mag), about twice a week, we measure gaseous production rates and the spatial distribution of several molecular species, including OH, CN, C_2, and C_3 (see Figure 4 for an example). In addition to providing the production rates of the different species through a proper photometric calibration, image analysis can reveal coma features (jets, fans, tails), that could lead to the detection of active regions and determination of the rotation period of the nucleus. Such regular measurements are rare because of the lack of telescope time on larger telescopes, yet are very valuable as they show how the gas production rate of each species evolves with respect to the distance to the Sun. These observations will allow the composition of the comets and the chemical class to which they belong (rich or poor in carbon chain elements for instance) to be determined, possibly revealing the origin of those classes. Indeed with about five to ten bright comets observed each year, this programme will provide a good statistical sample after a few years.

Broadband photometry is also performed once a week for fainter comets, usually far from the Sun, in order to measure the dust production rate from the *R*-band, to catch outbursts and find interesting targets for the main programme. Owing to the way the telescope is operated, the follow-up of split comets and of special outburst events is possible very shortly after an alert is given and can thus provide important information on the nature of comets. Light curves from these data are useful to assess the gas and dust activity of a given comet in order, for instance, to prepare more detailed observations with larger telescopes, especially the southern ESO telescopes. Hundreds of photometric and astrometric measurements of all the moving targets in our frames are reported each month to the IAU Minor Planet Center. Two new asteroids were found during a laboratory session with students of Liège University. The observatory code attributed by the IAU is I40.

Our first target was periodic comet 103P/Hartley 2, which made a close approach to Earth in October 2010 and was observed in great detail during the NASA EPOXI spacecraft flyby on 4 November. We monitored this small (2 km) but very active comet roughly every other night for four months and collected ~ 4000 frames

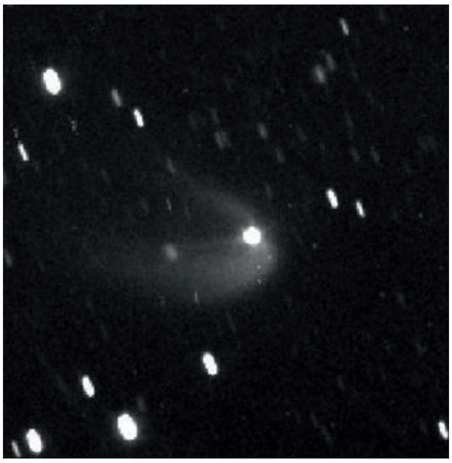

Figure 5. The TRAPPIST image of the the activated asteroid (596) Scheila taken on 18 December 2010.

through ten different filters. Our contribution to the worldwide campaign on this comet was recently published in Meech et al. (2011). The quality of the data allowed us to observe periodic variations in the gaseous flux of the different species from which we could determine the rotation of the nucleus and show that the rotation was slowing down by about one hour in 100 days (Jehin et al., 2010). This behaviour had never been so clearly observed before. The long-term monitoring of the production rates of the different species is nearly completed and will be combined with high-resolution spectroscopic data in the visible and infrared that we obtained at the ESO Very Large Telescope (VLT) to provide a clear picture of the chemical composition of this unusually active comet from the Jupiter family.

On account of the fast reaction time (a few hours), TRAPPIST is an invaluable instrument for catching rare and short-term events. As an example, the night after the announcement that asteroid (596) Scheila was behaving like a comet and could be a new Main Belt comet (only five of them are known — Hsieh & Jewitt, 2006), we began a programme to monitor the expanding coma and the brightness of the nucleus every night during a period of three weeks (see Figure 5 for one of the images). From imaging with TRAPPIST and spectroscopy with the ESO VLT we concluded that this behaviour was the result of a collision with a smaller asteroid in the Main Asteroid Belt and not the result of cometary activity (Jehin et al., 2010).

Among other related projects we joined an international collaboration whose goal is to catch rare stellar occultations by large trans-Neptunian objects (TNOs). This technique provides the most accurate measurements of the diameter of these very remote and poorly constrained icy bodies (provided at least two chords are observed). About one to two events per month are expected for a dozen big TNOs. On 6 November 2010, a unique observation was performed. A faint star was occulted by the dwarf planet Eris for 29 seconds. Eris is the most distant object known in the Solar System by far (three times the distance of Pluto) and supposedly the biggest TNO — it was even named the tenth planet for a few months in 2006. This was the third positive occultation by a TNO ever recorded and it allowed a very accurate radius for Eris (to a few kilometres) to be derived, providing a huge improvement in the determination of its size (previously known to within about 400 km). The surprise was to discover that Eris is a twin of Pluto and that it is not much bigger — remember that Pluto was demoted as a planet in 2006 because Eris was found to be bigger — both then received the new status of dwarf planets! A paper describing these results has been accepted for publication in *Nature* (Sicardy et al., 2011).

Perspectives

After only six months of robotic operations, TRAPPIST is already recognised in the exoplanet and comet communities as a unique tool on account of, among other things, the large amount of telescope time available under photometric conditions for performing time-consuming research. In particular, TRAPPIST has very quickly become a key element in the follow-up effort supporting WASP. In future, TRAPPIST will play a similar role for the successor of WASP, the Next Generation Transit Survey (NGTS)[5], a project led by Geneva Observatory and several UK universities, that will be installed at ESO Paranal Observatory in 2012. NGTS will focus on detecting smaller planets than WASP, and the high photometric precision of TRAPPIST will be a key asset for confirming and characterising these planets.

Further information and the latest news about TRAPPIST can be found on our web page[6].

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References

Csizmadia, Sz. et al. 2011, A&A, 531, 41
Deming, D. & Seager, S. 2009, Nature, 462, 301
Farnham, T. L. et al. 2000, Icarus, 147, 180
Gillon, M. et al. 2011, A&A (accepted)
Gillon, M. et al. 2007, A&A, 466, 743
Gillon, M. et al. 2009, A&A, 496, 259
Hsieh, H. & Jewitt D. 2006, Science 312, 561
Jehin, E. et al. 2010, CBET #2589
Jehin, E. et al. 2010, CBET, #2632
Mayor, M. et al. 2003, The Messenger, 114, 20
Meech, K. et al. 2011, ApJL, 734, L1
Queloz, D. et al. 2000, A&A, 354, 99
Sicardy, B. et al. 2011, Nature, accepted
Triaud, A. et al. 2011, A&A, 513, A24

Links

1 ESO PR on TRAPPIST: http://www.eso.org/public/news/eso1023/
2 Superwasp: http://www.superwasp.org
3 CoRoT: http://smsc.cnes.fr/COROT/index.htm
4 Comet Taxonomy, NASA workshop held 12–16 March 2011, Annapolis, USA
5 Next Generation Transit Survey: http://www.ngtransits.org/
6 TRAPPIST web page: http://www.ati.ulg.ac.be/TRAPPIST/Trappist_main/Home.html