Six Years of Science with the TAROT Telescope at La Silla

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The TAROT telescopes are a pair of robotic autonomous observatories with identical suites of instrumentation, with one located in each hemisphere. The southern TAROT telescope, which was installed in 2006 at the La Silla Observatory, uses more than 90 % of the clear night-time, and has become a very reliable and productive instrument. The primary objective of TAROT is the detection and study of the optical counter-parts of cosmic gamma-ray bursts, and many results have been obtained in this area. But several other topics, ranging from stellar physics to supernovae, have also been addressed successfully thanks to the telescope's flexibility. We present the main scientific results obtained by the TAROT robotic observatory at La Silla.

Figure 1. A wide-field image of the nearby early-type galaxy NGC 5128, which hosts the radio source Centaurus A, demonstrating the TAROT field of view of 2 by 2 degrees.

TAROT (Télescope à Action Rapide pour les Objets Transitoires — Rapid Action Telescope for Transient Objects) consists of two robotic autonomous observatories located at the ESO La Silla Observatory and at the Observatoire de la Côte d'Azur, Calern Observatory in France. They are 25-centimetre aperture telescopes with a field of view of 2 by 2 degrees (see Figure 1) and a pixel scale of 3.3 arcseconds. Images are recorded by an Andor 2k by 2k thinned CCD camera. With a six-position filter wheel, the user can choose between one of the *BVRI* filters, a special graded neutral density V filter and an open (clear) position. The equatorial mount can slew to any part of the sky in less than ten seconds (Klotz et al., 2008). The technical details of TAROT at La Silla have been presented by Boër et al. (2003). At present, the reliability of TAROT is such that more than 90% of the available time (i.e., cloudless night-time) is used for scientific observations.

Observation of gamma-ray bursts

The TAROT telescopes were designed in 1995 in order to catch the optical counterparts of gamma-ray bursts (GRBs). At that time, GRBs were known as short events (typically a few seconds) observed only by high-energy instruments on satellites. There were however theoretical predictions that GRBs should be also detectable at optical wavelengths (Rees & Meszaros, 1992). The design of TAROT was constrained by the large error boxes (more than 5 by 5 degrees) provided by the BATSE instrument aboard the Compton Gamma Ray Observatory (CGRO) satellite. In 1997 the BeppoSAX satellite observed the first X-ray afterglow (Costa et al., 1997) and could provide a precise position to the Nordic Optical Telescope (NOT) telescope which, in turn, recorded the first optical afterglow (van Paradijs et al., 1997).

Optical detection enables the GRB redshift to be measured. This was the ultimate proof that these objects originate from distant, cosmological sources. Current models of gamma-ray bursts involve either the disruption of a massive star with the fall-off of a transient accretion disc onto a newly born black hole and the emission of a powerful, highly relativistic collimated jet, or the coalescence of a binary system of compact objects (neutron star — neutron star or black hole — neutron star); see Gehrels & Mésáros (2012).

Figure 2. The TAROT La Silla telescope is located at the foot of the hill below the ESO 3.6-metre telescope in the former GMS building. Computers and electrical devices are stored in the adjacent shelter. The telescope does not require any human presence and observes every (clear) night.

Figure 3. The full Moon illuminates the TAROT observatory during a night in January 2007 when the great comet C/2006 P1 McNaught was visible with the naked eye.

TAROT Calern saw its first light in 1998. At about the same time, a rapid notification service profiting from all the internet capabilities, such as “sockets”, was created. The Gamma-ray Coordinates Network[1] (GCN) promptly distributes the coordinates of GRBs detected by satellites to ground facilities within a second or less. From 1998 to 2001, 21 CGRO–BATSE GRBs were monitored by TAROT Calern. The High Energy Transient Explorer II (HETE II) and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellites sent the triggers for the period 2001–2004. Swift[2] was launched in 2004 and sends about 100 GRB alerts per year within an error box of 6 by 6 arcminutes. The X-ray telescope and the Ultra-violet/Optical Telescope (UVOT) visible camera onboard Swift can reduce this uncertainty to a few arcseconds.

The second TAROT instrument was installed at ESO La Silla Observatory in autumn 2006. It is located in the former GRB Monitoring System[3] (GMS) building at the foot of the hill that is home to the ESO 3.6-metre telescope (see Figures 2 and 3). Since 2006, the pair of TAROT telescopes has covered the two hemispheres. The rapidly slewing mount makes it possible to start the optical observations before the end of the high energy prompt emission. Since 2001, 120 GRB triggers have been observed by both TAROT instruments. Ten of them were optically detected by TAROT during the prompt high energy emission, giving very important science data. Another advantage of TAROT early observations of GRBs is the rapid determination of an accurate position of the optical counterpart. This position can then be sent to large facilities such as the VLT, allowing for spectroscopy while the source is still bright enough, with 97 % of the GRB redshifts determined less than one day after the trigger.

During the first few minutes after the GRB trigger, the optical emission can display large variations on a timescale of a second (or even less). Classical experiments record a set of images, typically of 5 to 10 seconds duration, during the first few minutes. However, with a readout time of not less than 5 seconds, that means a dead time of 50 %! It is then impossible to obtain a continuous light curve, and hence to draw meaningful conclusions about the prompt emission part of the light curve, or even for flares during the afterglow of the GRB. We implemented as a workaround a specific operating mode: the first image, which lasts 60 seconds, is trailed in such a way that each star occupies a small ten-pixel track. If an object, such as the GRB source, is rapidly variable, this will be reflected in the trail corresponding to its position, allowing the derivation of a continuous light curve with a time bin of 6 seconds (Figure 4). The comparison of the brightness variation in the optical with the flux variation in gamma-ray energy gives precious information about the emission processes (Gendre et al., 2012). To our knowledge TAROT is the only instrument able to provide continuous light curves of the GRB events, i.e. without any dead-time for the

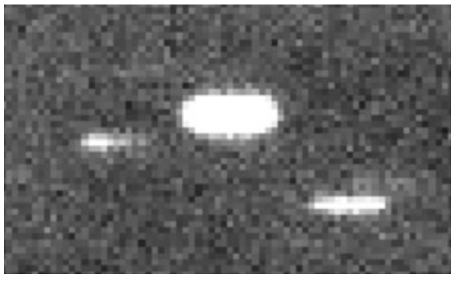

Figure 4. Trailed image of GRB 121024A. To obtain a time-resolved optical light curve during the first minute of the observation of a GRB, we trail the image such that each star occupies a small 10-pixel track on the frame. In this case TAROT observations started 45 seconds after Swift detected the event. The stars in the middle and right part of the image have a constant brightness during the exposure while the GRB optical counterpart is the left trail. At the start of the trail the brightness was R = 14.5 mag. At the end of the trail the magnitude had increased by 1.5 magnitudes only 60 seconds later! Just after this image, TAROT quickly provided the accurate position of the GRB allowing spectroscopy to be obtained with the VLT X-shooter spectrograph less than two hours later (Tanvir et al., GCNC 13890). The redshift of the source is 2.3, corresponding to an event that occurred 10.8 billion years ago.

first minute. Because of the very rapid intrinsic variability of GRBs, this feature is very important and allows us to draw significant conclusions by comparison between the gamma-ray signal and the optical emission as seen by TAROT.

Thanks to the presence of other experiments on the same site, namely GROND (Greiner et al., 2007) and REM (Chincarini et al., 2008) the ESO La Silla Observatory provides a unique set of instruments that work together to observe the optical counterparts of GRBs. TAROT and REM are rapid telescopes that can record the first few minutes of the GRB events. After this, the GROND instrument can detect very faint counterparts. During the last nine years (the SWIFT era) major advances in GRB science have come from using the data from these instruments.

Space environment, Solar System and stellar astronomy

Although GRBs are the primary objective of TAROT, because of the scarcity of their occurrence (an alert per week on average) and short duration, the time devoted to the observation of GRBs is short compared to the night-time duration. This allows ample time to study other objects which benefit from the high throughput and flexibility of TAROT. One of these programmes addresses the measurement of the pulsation periods of Galactic RR Lyrae stars. About 400 stars are monitored. The goal is to monitor period variations and study the Blazhko effect, a modulation of pulsation period and amplitude which is not yet understood (Figure 5). In 2007 we published a study on period variations on a time baseline exceeding a century (Le Borgne et al. 2007). More recently we published an analysis of the Blazhko effect for a large sample of RR Lyr stars (Le Borgne et al., 2012).

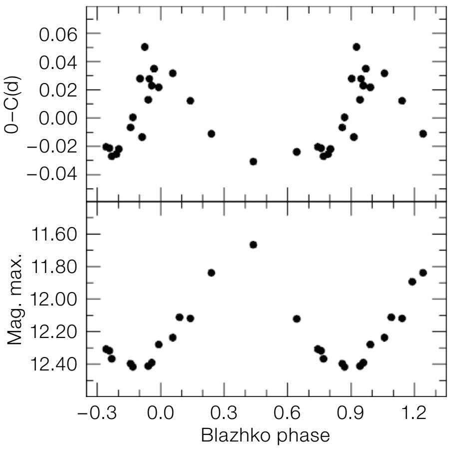

Figure 5. RR Lyrae stars in the Galaxy are observed by TAROT in order to understand the origin of the Blazhko effect. Each dot on the plot represents a light curve characteristic of the RR Lyr star XY Eri over a night (figure from Le Borgne et al., 2012). The Blazhko period is 41.22 days. The upper plot represents the delay between the times of the maximum of light and the mean value. The bottom plot represents the magnitude at the maximum of light against the Blazhko phase. This effect is monitored for 400 RR Lyrae stars.

With the widespread use of space for many activities (telecommunications, remote sensing, meteorology, etc.), the issue of orbital debris has become very sensitive. Several satellites have been lost because of a collision with debris, often of centimetre size; and it is expected that the situation will become worse within a short time, as more satellites are launched, and the risk of catastrophic collisions increases exponentially. Some orbits, like the geostationary orbit, have also become very crowded, implying that satellites have to be maintained in their orbital slot and their position has to be known with a very high accuracy. The use of radar has the advantage of allowing good precision for ranging, with the disadvantage of being less precise for the angular position; however radar measurement requires a lot of power for these high orbits. Small telescopes can give very accurate solutions. We use TAROT to monitor the position of several geostationary satellites with a high accuracy, and to survey the orbital debris. About 20 000 astrometric positions of geostationary satellites are gathered by TAROT each month. The process (observation, image processing for satellite extraction and astrometric reduction) is fully automated without any human in the loop.

Occultations of stars by minor planets provide a very accurate method to determine the dimensions of asteroids. However, even with a very precise prediction, it is impossible to forecast with enough accuracy the path of the shadow on the Earth. TAROT is among the few telescopes that can easily monitor a star for a possible occultation. In practice we record all the predicted occultations that occur within less than 1000 kilometres from the telescope. Ninety-second images are taken with no sidereal motion. The star occulted appears as a trail with a gap if we have been lucky enough to catch the occultation (as was the case for the image shown in Figure 6). Sixty such occultations have been measured[4]. The duration of the gap can be converted to a length and gives constraints on the size of the minor planet. The date of the occultation also provides its astrometric position with an error generally less than 100 milliarcseconds.

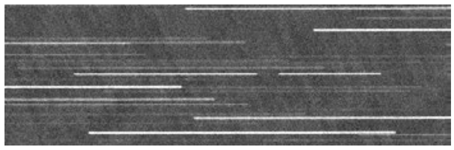

Figure 6. TAROT La Silla recorded this image without any diurnal motion and stars appear as trails. The trail in the centre of the image is of the star TYC 0611-00505-1 which was occulted by the asteroid (227) Philosophia for 6.41 seconds on 6 November 2011. This duration corresponds to an asteroid size of 74 kilometres.

Extragalactic studies

The discovery of supernovae (SNe) on the rise is a very important topic, both to understand the physics of the explosion and for their use in the determination of distances in the Universe. We decided to start a programme aimed at the earliest possible detection of nearby SNe. Four hundred nearby galaxies are monitored each night, and the same field is observed every three days. Two observation campaigns were carried out in 2007 and in 2012. Eight supernovae were discovered. The most interesting one of them was 2012fr, which exploded in the nearby spiral galaxy NGC 1365 (Figure 7). As the galaxy was observed in detail by the Hubble Space Telescope before the explosion, it is possible to constrain the brightness of the progenitor. SN 2012fr is a Type Ia supernova that was discovered by TAROT — La Silla less than two days after the explosion ignited, giving crucial data for models of supernovae. The light curve of SN 2012fr

Figure 7. TAROT image of the barred spiral galaxy NGC 1365 showing the supernova 2012fr discovered with TAROT as the blue source just above the nucleus of the galaxy. SN 2012fr was the brightest apparent supernova of 2012.

observed by TAROT shows that the decay in the *B*-band is very slow compared to the standard value. Investigations are continuing since the supernova will be observable for the whole of the year 2013. Everyone can contribute to this programme and has a chance to discover a supernova using the dedicated tool SN_TAROT[5].

Serendipitous science

We have launched a large scientific programme which consists of extracting the magnitudes of all the objects in all the images taken at both telescopes. For that purpose we have constructed an archive of the images which resides on the CADOR computer at the Observatoire de Haute-Provence, France. A first extraction was done in the period 2005–2007 using images of TAROT Calern only and a catalogue of 1175 new periodic variable stars was published (Damerdji et al., 2007). Now more than one million TAROT images are stored in the CADOR database. A major effort is underway to make a full analysis of the images, and to update the catalogue.

The Institut de Mécanique Celeste et de Calcul des Ephémerides (IMCCE) makes use of these images to extract the astrometric positions of known asteroids. In turn these positions are used by the SkYBOT virtual observatory service and 30 000 asteroid positions were extracted in 2012.

Education and Public Outreach

TAROT is also used by high school teachers who conduct science projects with their students. Examples of such programmes include the determination of the age and distance of star clusters using TAROT images, the monitoring of the position of satellites of giant planets to determine their mass, or the observation of supernovae to determine their type and distance from their light curve.

Prospects

Since 1998, the TAROT network of telescopes has contributed actively to GRB science. Its major contribution has been its unique capability to monitor the first few minutes of the optical emission. Its initial goals have been reached and even surpassed and 30 refereed papers have been published using TAROT data. Although TAROT will continue to work on this topic, we are also preparing actively for the new horizons of multi-messenger astronomy.

TAROT is already connected to the ANTARES experiment, a neutrino telescope consisting of lines of photomultipliers installed in the depths of the Mediterranean Sea. TAROT also participated in the 2010 campaign to follow up the triggers provided by the gravitational wave (GW) interferometers LIGO and VIRGO, and has successfully passed the blind tests (Abadie et al., 2012). The next generation of GW detectors will be ready in 2017 and TAROT will get ready to participate in this exciting new adventure. At the same time TAROT has been the seed for an effective automated network of heterogeneous telescopes around the world, and we are finding ways to complement and enhance the observation of the fast transient sky from the Earth.

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Links

[1] Gamma-ray Coordinates Network: http://gcn.gsfc.nasa.gov
[2] Swift: https://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html
[3] GRB Monitoring System (GMS): http://www.eso.org/public/teles-instr/lasilla/grb.html
[4] Listing of TAROT minor planet occultations: http://www.euraster.net/tarot/
[5] Supernova hunting with SN_TAROT: http://cador.obs-hp.fr/sn_tarot/