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THE BOOTES EXPERIMENT IN SUPPORT OF THE GRAN TELESCOPIO CANARIAS (GTC) IN THE STUDY OF THE HIGH ENERGY UNIVERSE

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RESUMEN

Un programa de observaciones de oportunidad (OdO) para seguir las posluminiscencias de Brotes de Rayos Gamma (BRG) será una herramienta muy potente en el estudio del Universo primitivo, ya que la fotometría y la espectroscopía de BRG son instrumentos muy adecuados para trazar la tasa de formación estelar del Universo a altos corrimientos al rojo (las observaciones tempranas en el visible y el IR cercano con el GTC pueden detectar BRG hasta $z \lesssim 17$; Castro-Tirado y otros, este volumen. pág. 252; Gorosabel y otros, este volumen, pág. 288). BOÓTES (Brotes Observados y fuentes Ópticas Transitorias Exploradas Sistemáticamente) puede apoyar muy eficientemente a un OdO del GTC gracias a su capacidad de actuar de forma robótica y extremadamente rápida. En este artículo cubrimos los pasos ya dados, y los todavía pendientes, para completar un sistema de análisis de datos automático, en línea, y en tiempo real, para BOÓTES. Dicho sistema será capaz de proporcionar posiciones tempranas, fiables y exactas de BRG (confirmadas por satélite) para activar un OdO del GTC.

ABSTRACT

A GTC target of opportunity program (ToO) for gamma ray burst (GRB) afterglows will be a very powerful tool for studying the primitive Universe. Photometry and spectroscopy of GRBs are very suitable for tracing the star formation rate of the Universe at high redshifts (prompt optical and near-infrared observations with the GTC could detect GRBs to $z \lesssim 17$; Castro-Tirado et al., this volume, p. 252; Gorosabel et al., this volume, p. 288). BOOTES (Burst Observer and Optical Transient Exploring System) can very efficiently support a ToO at the GTC through its robotized, extremely fast response capabilities. In this paper, we discuss the ongoing effort to finalize a real time, online, automatic data analysis system for BOOTES. Such a system will be able to provide early, reliable, and accurate GRB positions (confirmed by satellite) to trigger a GTC ToO.

Key Words: **ASTROMETRY — GAMMA RAYS: BURSTS — GAMMA RAYS: OBSERVATIONS — TECHNIQUES: IMAGE PROCESSING — TELESCOPES**

1. INTRODUCTION: GRBS

GRBs were first reported by Klebesadel et al. (1973) as they studied data acquired by the *VELA* spacecraft (see also Bonnell & Klebesadel 1996). Bursters reveal themselves as brief flashes of cosmic photons, emitting most of their energy above ≈0.1 MeV, and are isotropically distributed (Mazets et al. 1981; Atteia et al. 1987; Meegan et al. 1992). The distribution of the sources is not homogeneous as derived from the $\log N$–$\log S$ diagram. Rather, a deficiency of weak events is present; the distribution deviates from the $-3/2$ slope of the straight line for a uniform distribution in Euclidean space (Meegan et al. 1994). This isotropy suggested, in the early 1990s, a cosmological origin (at least for most GRBs).

GRBs show no periodicity in their occurrence but they show time structure: ∼25% (harder spectrum) last about 0.2 s, ∼75% (softer spectrum) last about 30 s (Fishman & Meegan 1995; Kouveliotou et al. 1993). The first counterparts were detected in 1997, 3–20 hr after the onset of the burst. Counterpart detections have been made to date in the X-ray, optical, infrared (IR), and radio bands. These detections at longer wavelengths are critical to gaining a better understanding of GRBs because the source cannot be seen directly. For the optical case the luminosity declines as a power law with $F \propto t^{-\alpha}$ ($0.8 < \alpha < 2.3$; $\langle\alpha\rangle = 1.35$). Their spectra confirmed a cosmological origin (Metzger et al. 1997). See Castro-Tirado (2001 b,c) and Castro-Tirado et al. (2001a) for a re-

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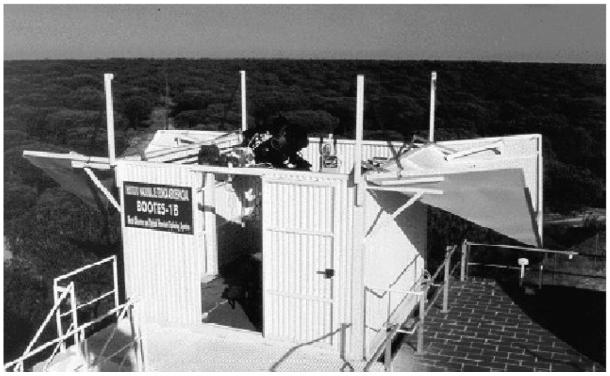

Fig. 1. BOOTES-1B dome housing one of the 30 cm Schmidt–Cassegrain telescopes and a few of the WFCs at the Centro de Experimentación del Arenosillo, in Mazagón, Huelva, Spain.

view.

2. BOOTES

BOOTES (Castro-Tirado et al. 1996), mostly a Hispano–Czech international collaboration, is a pioneer robotic astronomical observatory. Equipped with wide field charge coupled device (CCD) cameras (WFCs) and 30 cm telescopes, it fills the gap which exists in the field of rapid variability astronomy. BOOTES especially aims at the detection and study of the optical transients (OTs) that are generated in conjunction with the elusive GRBs (Castro-Tirado et al. 1999). It is also part of the ground segment for the ESA's *International Gamma Ray Laboratory satellite* (*INTEGRAL*; Hudec et al. 1999). Since first light in 1998 BOOTES has provided follow-ups for more than 60 events with the first of its observatories (Castro Cerón et al. 2001 a,b,c). The most important results obtained so far are: a) the detection of an OT in the GRB 000313 error box (**?**); b) non-detection of optical emission simultaneous to the GRB 010220 event (Castro-Tirado et al. 2001a; de Ugarte Postigo et al. 2002). Additionally, BOOTES has accumulated an enormous database of sky images to study objects with exhibit short-lived variations.

BOOTES-1, the main BOOTES observatory, is located in Mazagón (Huelva), a dark-sky area in southwest Spain, and is hosted by the Instituto Nacional de Técnica Aeroespacial Esteban Terradas in its Centro de Experimentación del Arenosillo. It has two domes (BOOTES-1A and BOOTES-1B) that shelter two Schmidt–Cassegrain telescopes and several WFCs (see Figure 1). All the instruments carry out complementing systematic explorations of the sky each night (Castro Cerón et al. 2001 a,b,c).

A second observatory (BOOTES-2) has been recently inaugurated 240 km east of BOOTES-1 at La Mayora, an experimentation center, property of the Co nsejo Superior de Investigaciones Científicas, in Costa del Algarrobo (Málaga). BOOTES-2 is both identical and uses the same instrumentation as BOOTES-1B. Observing the same field of the sky simultaneously from both locations, BOOTES has a stereoscopic view. Thus, using parallax, it can discriminate against satellite glints and other atmospheric and near-Earth detected sources up to a distance of 10^6 km (Castro-Tirado et al. 1996).

The set-up completes the Burst Alert Robotic Telescope, which uses commercially available hardware components (Soldán et al. 1998; Hudec et al. 2001, 2002), and the *Optical Transient Monitor*, in operation at the Astronomical Institute in Ondřejov, Czech Republic.

BOOTES has implemented a remote information and control system in collaboration with Groupe Spécial Mobile (GSM) tools. A communication protocol between a personal computer and a GSM modem, via Recommended Standard 232, based on the Short Message Service standard (version 03.40) and programmed in the LabView environment, has been developed. It allows full remote control of the observatories with no extra staff (Mateo Sanguino 2001).

3. SCIENTIFIC OBJECTIVES

What originates a GRB still remains a puzzle. It is of the utmost importance, in order to solve this puzzle, to perform prompt optical follow-up observations to detect longer-wavelength transient emission associated with GRBs. BOOTES aims at finding optical counterparts to GRBs. Such a search poses two problems: gamma rays permit only limited spatial resolution, resulting in large errors in the localization of sources, and GRBs last for a very short time. BOOTES can perform automatic rapid follow-up observations in the visible with its WFCs, thus overcoming these two problems. Its main scientific objectives include (Castro-Tirado et al. 1999):

- Simultaneous and quasi-simultaneous observations of satellite-detected GRB error boxes.
- Detection of optical flashes of cosmic origin.
- Sky monitoring in the I, R[9], and V bands.
- Search for recurrent transient optical emission.
- Potential discovery of different types of objects.

[9]BOOTES' CCD cameras peak in the red, so the R band must not be taken as a standard filter. See http://www.laeff.esa.es/BOOTES/ for more information.

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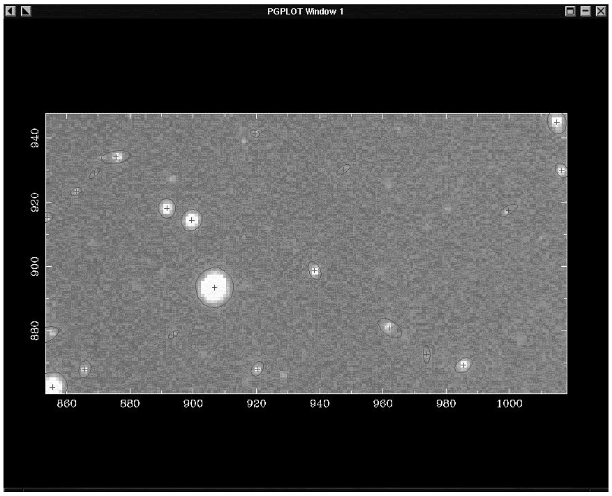

Fig. 2. Screen capture blow-up showing a snapshot of the pipeline right after performing step 3. All starlike objects present in the image have been marked down with a "+" sign after ellipse fitting and flux photometry search.

4. AUTOMATIC DATA ANALYSIS

The GTC and its scheduled first-light instrumentation will have unique capabilities to study GRBs through ToOs. BOOTES' robotized, extremely fast response can efficiently support a ToO on the GTC. For this purpose, the BOOTES team has embarked on the development of an automatic data analysis system that will allow for real time, on-line, reduction and analysis of the scientific images acquired by BOOTES' WFCs in follow-up observations to a spacecraft GRB detection. Such automatic data analysis system will be critical to activate a GTC GRB ToO at a stage early enough to make a difference. Operations will run as outlined below:

Spacecraft GRB alert: A spacecraft GRB detection is made and the appropriate coordinates, which mark the GRB location and the surrounding error box, are transmitted to BOOTES' computers via the GRB Coordinates Network (Barthelmy et al. 1998). Robotized rapid pointing and automatic image acquisition with BOOTES' WFCs commences at once at the different stations.

Pipeline 1 (image reduction): Automatic, on-line image reduction is performed locally and dark frames are subtracted from the scientific images. The latter are then divided by flatfields.

Pipeline 2 (sky correction): The sky background flux and error in its determination are calculated.

Pipeline 3 (new object search): A search is made for all starlike objects present in the reduced scientific images. The search is performed using ellipse fitting and flux photometry to discard objects such as meteors, saturated stars, etc. (see Figure 2).

Pipeline 4 (astrometry): The ~ 100 brightest objects in each reduced scientific image are compared with the corresponding ones in a catalogue. A polynomial fit is performed. The nominal error should be less than half a pixel, typically a quarter of a pixel ($\approx 10''$ for our $16^\circ \times 11^\circ$ frames), sufficient precision for imaging on a 10 m class telescope. Here, we are confronting problems such as lens deformation of the field of view and telescope pointing errors.

Pipeline 5 (photometry): The coordinates are obtained from the previous step and the closest object is chosen from a catalogue, then a magnitude value is assigned. A statistical correspondence is expected from linear fitting. Here we are confronting problems such as the fact that, currently, catalogues are not available for all of BOOTES' filters.

Pipeline 6 (cross-correlation): Typically, 20 to 30 "new objects" per image result up to step 5; after cross-correlation of simultaneous images from two different cameras, these all disappear. If any of the new objects survive, cross-correlation with the second station is performed. If the source still survives, the object is considered real. Final pipeline output is a small text file, which transfers easily over the Internet in real time The automatic data analysis system is now operational on the BOOTES-1 station. At present, it takes 7 min per image to run the whole automatic data analysis process. Fine-tuning is in progress. The goal is to lower the time required to fully process one image to 1 min. This goal is expected to be reached during the summer of 2002.

BOOTES' automatic data analysis system will be able to provide reliable and accurate GRB positions (confirmed by satellite) with unmatched readiness, thus allowing for a timely and efficient triggering of a GTC GRB ToO. It will also identify other new objects for further study.

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