

## SPECTRO-IMAGING FOLLOW-UP OF GAMMA-RAY BURSTS WITH THE OHP/T193

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**Abstract.** Gamma-ray bursts (GRBs) are the most powerful explosions known in the Universe produced by the death of massive stars or the coalescence of two compact objects such as a binary system of two neutron stars. Due to their transient nature, rapid follow-up observations are the unique chance to fully characterize their radiative processes and better understand these violent phenomena. The upcoming Sino-French SVOM mission will monitor the gamma-ray sky and detect new transient sources such as GRBs. In addition to previous GRB missions, SVOM will benefit from an improved synergy with ground telescopes to perform fast and efficient follow-up observations. As part of this effort, we proposed a target of opportunity program using the spectro-imager MISTRAL instrument mounted on the OHP/T193 to follow-up GRB alerts. Our program was granted for 10-15 alerts (20-30 hours) over the past three semesters since March 2022. We present our first GRB follow-up observations with MISTRAL using Swift alerts. In particular, we report the observations of the brightest of all time GRB (GRB 221009A) and a first GRB redshift tentative with the OHP/T193. These preliminary MISTRAL triggers prepare the SVOM community to react quickly to alerts, and rapidly reduce, analyze and interpret the MISTRAL data, essential to fully exploit the imminent SVOM alerts.

Keywords: Gamma-ray bursts, Follow-up, MISTRAL, SVOM

### 1 Introduction

Gamma-ray bursts (GRBs) are brief flashes of  $\gamma$ -photons produced by extragalactic explosions. Observationally, two main emissions are detected, a prompt emission mainly composed of gamma-ray radiations from milli-seconds to minutes followed by a longer (hours to days) and spectrally broader (X-ray to radio) afterglow emission. The GRB population is traditionally divided into two main classes according to their hardness and duration considering a separation at  $T_{90} \sim 2$  s (e.g., Sakamoto et al. 2011). Short and hard GRBs are thought to be produced by the coalescence of two compact objects (e.g., a binary neutron star system) (Abbott et al. 2017) while long GRBs are thought to be associated with the core-collapse of a fast rotating massive stars (Hjorth et al. 2003). Rapid and efficient follow-up observations represent the only way to further characterize the transient by improving its localization, inferring its distance (i.e., redshift), and sampling the evolution of its light curve. The forthcoming Sino-French SVOM (Space-based multiband astronomical Variable Objects Monitor) mission will be dedicated to the study of GRBs (Wei et al. 2016). The mission includes a major follow-up network to improve the space-ground synergy and the wavelength coverage of the afterglow emission. SVOM is expected to provide a more homogeneous and complete sample (e.g.,  $\sim 2/3$  redshift) than previous missions. In this work, we report the first follow-up observations of GRBs carried out by the spectro-imager MISTRAL mounted on the OHP/T193 telescope. These observations provide valuable experience for preparing upcoming SVOM alerts.

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## 2 Spectro-imager MISTRAL

The Haute-Provence Observatory (OHP) is located in the south-eastern of France at about 650 m altitude with observational conditions favorable in more than 60% of the nights. The main telescope still in operation for science is the T193 with a primary mirror of diameter 1.93m. Two main instruments are permanently mounted on the telescope and can be switched in less than one minute, the high resolution SOPHIE spectrograph and the Multi-purpose InSTRument for Astronomy at Low-resolution (MISTRAL) spectro-imager. MISTRAL offers an imagery mode as well as a low-resolution spectroscopy mode using an elongated and narrow slit ( $R \sim 750$ ) through two independent settings, a blue grism (4200-8000 Å), and red grism (5800-9950 Å)\*. Since 2022, the instrument was opened to the community for visitor mode and target-of-opportunity (ToO) mode limited at 2 hours per trigger with one ToO maximum every 3 nights. Given the unpredictable nature of GRBs, the ToO mode is ideal for GRB science and commonly used with ground telescopes to perform follow-up observations of new sources detected by gamma-ray space missions.

## 3 Scientific motivation

Two meters type telescopes are more likely to be available than large (>8 m) ground telescopes. The OHP/T193 is also ideally located between two others SVOM follow-up telescopes (in China and Mexico). MISTRAL can reach in a reasonable time a magnitude of about 20.5 mag for photometry (~20 mins) and 19 mag for spectroscopy (~60 mins) with a minimal signal-to-noise ratio (S/N) of 3. Moreover, considering previous observed GRBs in the R-band (Kann et al. 2010), we expect to be able to detect with MISTRAL most of GRBs, if observed relatively soon after their first detection from space satellites (typically <4 hours). In a small number of cases, if the afterglow is bright enough (<19 mag) or if observations are carried out promptly after the GRB trigger time, we can obtain a spectrum of the source with a good S/N and infer its redshift using absorption lines in the afterglow emission. Finally, for local events, we might also constrain the presence of a possible supernova (SN) as previously observed with long GRBs (Hjorth et al. 2003), as well as deeply characterize the host galaxy after the fading of the transient.

## 4 Follow-up strategy

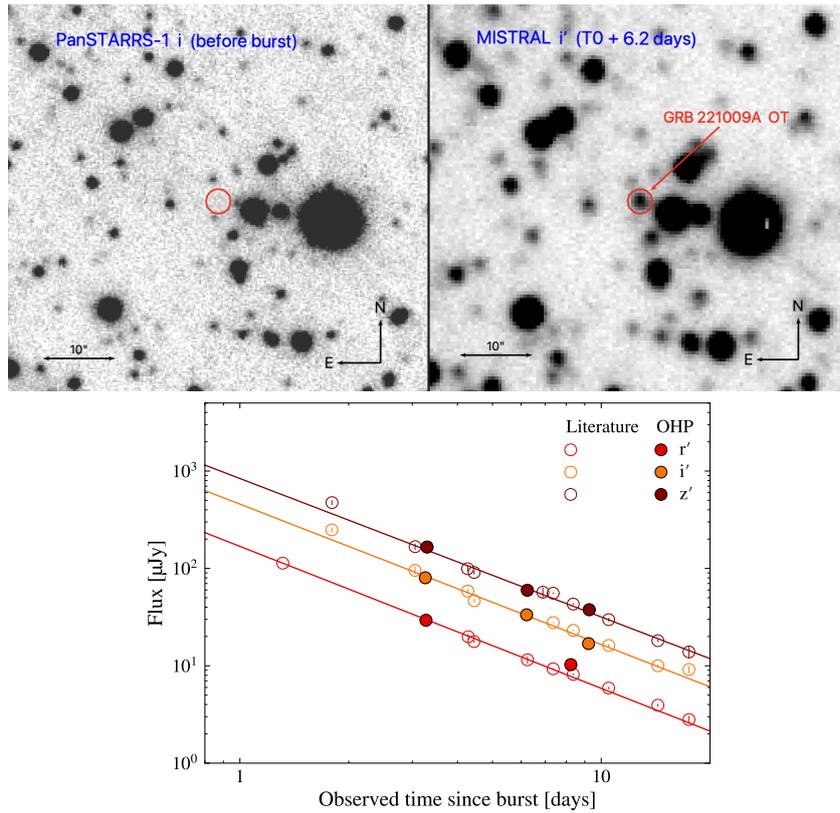
Multiple GRB alerts are reported every day by various gamma-ray spacecrafts with diverse localization accuracy, from arcseconds up to several degrees. Given the field-of-view of MISTRAL (5 arcmin) and the expected localization of SVOM GRBs (<2 arcmin in the majority of cases thanks to MXT, Götz et al. 2023; Schneider et al. 2023), we limit our program to GRBs detected by the *Swift* satellite with sub-arcmin localization provided by the X-Ray Telescope (XRT). This maximizes our ability to find the optical transient and practice ToO observations in similar conditions than during the SVOM operations. Our trigger criteria can be summarized as follow: (1) *Swift* alert with at least an XRT detection (error box  $\lesssim 10$  arcsec), (2) Visibility >1 hour above 30° at OHP, (3)  $T_{\text{obs}} < T_0 + 4$  hours, (4) Low Galactic extinction:  $A_V < 0.5$ , (5) No nearby bright stars. In practice, these criteria can be relaxed for interesting events or regarding information reported by other teams via Gamma-ray Coordination Network (GCN) circulars<sup>†</sup>. During observations, a quicklook of the data are performed in real-time by the burst advocates in shift using static data calibration files. This allows us to rapidly adapt the observational strategy and maximize the scientific results. A typical observation sequence starts by ~20 mins of imaging in the R-band. If a bright counterpart is identified (<19 mag), MISTRAL switches to spectroscopic mode for 60 minutes. Alternatively, imaging mode is continued to increase the S/N, and eventually observations in additional bands can be performed to further constrain the afterglow light curve.

## 5 First GRB follow-up and results

Over the three past semesters, MISTRAL was triggered a total of nine times with a mean response time of ~15 hours and included imaging and spectroscopy observations. Our resulting photometry and analysis were reported to the GRB community via GCN circulars. We have detected 3 optical transients (Schneider et al. 2022a; Turpin et al. 2023a; Adami et al. 2023a), inferred 2 redshifts (Adami et al. 2023b,c), and derived 5

\*[http://www.obs-hp.fr/guide/mistral/MISTRAL\\_spectrograph\\_camera.shtml](http://www.obs-hp.fr/guide/mistral/MISTRAL_spectrograph_camera.shtml)

<sup>†</sup><https://gcn.nasa.gov/circulars/>

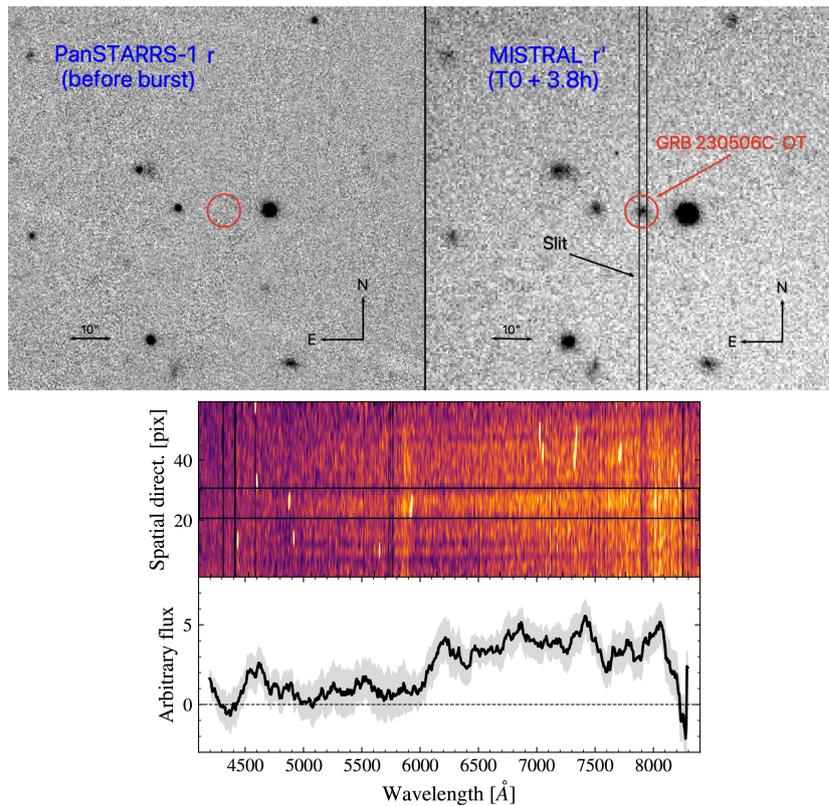


**Fig. 1. Top:** Optical counterpart of GRB 221009A (the BOAT) detected by MISTRAL. The left panel shows the PanSTARRS-1 image of the GRB 221009A field before the burst and the right panel is the image obtained by MISTRAL of the same field  $\sim 6$  days after the detection of the burst by the Fermi satellite. The expected optical transient position is highlighted by a red circle. **Bottom:** Light curve of GRB 221009A combining literature (empty circles) values and measured obtained at the OHP with MISTRAL and OHP/T120 telescope at different epochs for  $r'$ ,  $i'$  and  $z'$  filters.

upper-limits up to  $r > 22.3$  AB mag (Schneider et al. 2022b; Turpin et al. 2022, 2023b; Adami et al. 2023a,d). Among them, GRB 221009A (also called the BOAT for the brightest of all time) was observed at two different epochs ( $T_0 + 6$  and  $T_0 + 10$  days) by MISTRAL in multiple filters. The optical afterglow was clearly detected in both epochs, as visible in the top panel of Fig. 1. Our magnitudes contributed to the extensive follow-up of this source and confirmed the power law decay expected for a pure afterglow fading (Fig. 1). This further helped to investigate the possible raising of the SN, widely debated within the community for this burst. GRB 230506C was rapidly observed after the *Swift* trigger (about  $T_0 + 4$  hours). A clear optical transient at  $\sim 20.9$  mag in the r-band was detected in the XRT error circle (top panel of Fig. 2). We then obtained a spectroscopy observation of 30 mins using the MISTRAL blue setting. The spectrum revealed a faint continuum consistent with the source. A refined analysis of the 1D spectrum revealed break at  $\sim 6000$  Å (Fig. 2). We interpreted it as the Lyman- $\alpha$  break, commonly observed in GRB afterglow spectrum due to neutral hydrogen absorption within the host galaxy. This suggests that the redshift of this source is around  $3.7 \leq z \lesssim 4$ . This represents the most distant redshift measured at OHP and confirm the capability of MISTRAL to infer the redshift of GRBs.

## 6 Conclusions

We reported the first follow-up observations performed with the MISTRAL instrument as part of our GRB program. A total of nine observations were carried out based on *Swift* alerts and our data analysis were reported to the community via GCN circulars. These triggers demonstrated the potential of MISTRAL to constrain the light curve or redshift of GRBs, and its possible key role for the SVOM follow-up network. These first ToO observations also provided valuable training, from initial reaction to data interpretation, in order to be ready for the imminent SVOM alerts.



**Fig. 2.** **Top:** Optical counterpart of GRB 230506C detected by MISTRAL. The left panel is the PanSTARRS-1 image of the GRB 230506C field where no source is visible in the red circle. The right panel shows the image obtained by MISTRAL of the same field at  $\sim 4$  hours after the detection of the burst by *Swift*. The long slit position used for spectroscopy observation is visible as a black box and the expected optical transient position is highlighted by a red circle. **Bottom:** 2D spectrum (top panel) obtained by MISTRAL of GRB 230506C in blue setting. The black box shows the extraction region considered for the 1D spectrum visible in the bottom panel.

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