The VLT Rapid-Response Mode: implementation and scientific results

Paul M. Vreeswijk[a,b], Andreas Kaufer[c], Jason Spyromilio[d], Ricardo Schmutzer[c], Cédric Ledoux[c], Alain Smette[c], Annalisa De Cia[b]

[a] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen

[b] Centre for Astrophysics and Cosmology, Science Institute, University of Iceland, Dunhagi 5, 107 Reykjavik, Iceland

[c] European Southern Observatory, Alonso de Córdova 3107, Vitacura, Santiago, Chile

[d] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748, Garching, Germany

ABSTRACT

The Rapid-Response Mode (RRM) at ESO's Very Large Telescope (VLT) allows for rapid automatic observations of any highly variable target such as Gamma-Ray Burst (GRB) afterglows. This mode has been available for various instruments at the VLT since April 2004, and can be easily implemented for any new instumentation. Apart from discussing the operational side of this mode, we also present VLT/UVES GRB afterglow spectra observed using the RRM, which show clear variability of absorption lines at the redshift the GRB host galaxy. Without the RRM this variability would not have been observed. Using photo-excitation and -ionization modelling, we show that this varibility is due to the afterglow flux exciting and ionizing a gas cloud at distances varying from tens of parsecs to kiloparsecs away from the GRB.

Keywords: SPIE Proceedings, gamma-ray burst afterglows, automated observations, high-resolution spectroscopy

1. INTRODUCTION

The Rapid-Response Mode (RRM) at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) provides the means to point the 8.2 m unit telescopes in a completely automated fashion. This mode was mainly motivated by the discovery of very bright and distant Gamma-Ray Burst (GRB) afterglows, e.g. the case of GRB 990123,[1] which reached 9th magnitude in the visual band while originating at a redshift of $z = 1.6$. This brightness was more recently superseded by GRB 080319B at $z = 0.937$, which reached an incredible V=5.5.[2] Although they can be extremely bright at early times, i.e. within a minute or two from the gamma-ray trigger, their luminosity tends to fade with a power law with an index of −1 to −2, and therefore it is crucial to react swiftly in order to be able to observe the afterglow when it is still bright. There are numerous smaller telescopes that automatically react to the GRB triggers, currently provided by the very successful Swift satellite mission, ranging in size from 0.5–2 m, a.o. ROTSE, SuperLotis, RAPTOR, REM, TAROT, the Liverpool and Faulkes telescopes, ESO/MPI 2.2m. (We note that the GROND instrument at the ESO/MPI 2.2m at La Silla has been fitted with a system very similar to the RRM, which has led to various exciting results, including the $z = 6.3$ redshift determination for GRB 080913.[3] In this paper we focus on the VLT RRM.) To our knowledge the VLT is the only 8-10 m class telescope that can react fully automatically. In this talk we present this mode, explains how it works, and discuss scientific results made possible through the RRM.

Further author information: Paul Vreeswijk: E-mail: pmv@dark-cosmology.dk

2. THE IMPLEMENTATION OF THE VLT RAPID-RESPONSE MODE

The RRM is triggered by members of a team that were awarded observations (in the form of RRM triggers) for that particular semester, or period in ESO jargon. The preparation of the observations is practically the same as normal ESO service-mode programs, in the sense that a description of the observation, i.e. target location, exposure time length, choice of filter/grism, etc., has to be prepared before the start of the period. The only difference being that RRM programs, as ESO's Target-of-Opportunity (ToO) programs, do not need to provide the object position or finding chart.

It is the user who decides when the RRM is triggered. If the time passed since the transient event (e.g. GRB) is more than 4 hours, the normal ToO procedures should be used, as this time delay does not anymore justify the interruption caused at Paranal. The RRM can interrupt both service mode and visitor mode observations. In service mode, the interruption is naturally absorbed by the service mode queue observations. In visitor mode, the visitor is compensated during service mode time immediately after the run, with the highest priority, and with the same or better weather conditions than that at the time of the RRM activation. The RRM system can be put offline at any time during the night if so desired, e.g. when a highly time-critical program is being executed with a higher priority than a GRB RRM observation.

To trigger the RRM, the user needs to send an ftp file to a FTP server at ESO in Garching. The name of this ftp file contains an identification of the program, the name of the instrument to be activated and which observation block (OB, a description of the observations in ESO jargon) to use, while the content of this file specifies the location on the sky in RA and DEC. A program running at Paranal observatory is constantly monitoring this FTP server, and if it detects a file, it starts to perform a number of checks.

First, the RRM system has to be up and running; this is done at the start of the night by the night astronomer. Second, the program ID and requested observation description has to match a list of pre-approved combinations of IDs and descriptions; this list is prepared by the Paranal staff on the first day of the period. Each VLT unit telescope has four different foci: one Cassegrain, two Nasmyth, and one Coudé for the VLTI. To change from one focus to another takes about 10 minutes, and it was decided that if the focus is not set to the instrument that is requested, the RRM trigger is not accepted. Additionally, a number of smaller checks are made, such as the night time check (sun is at least -12 degrees below the horizon), observability of the object, distance to the moon, and in case of near-IR observations: the brightness of stars around the requested position to avoid burning the CCD.

If all these checks are verified, an alarm will go off in the VLT control room alerting the night astronomer and telescope and instrument operator of the RRM trigger. A pop-up window warns them that the telescope will start moving in 30 seconds. Should it happen that somebody is close to the telescope in the dome while all systems are online (this should normally not be the case), the RRM activation can be terminated within these 30 seconds. Meanwhile, the object RA and DEC is taken from the ftp file by the RRM program and added to the observation description, ready to be executed. After the 30 seconds (or earlier through RRM activation confirmation by the telescope staff), the RRM program will finish the observation that was on-going at the time of the RRM trigger (but makes sure to save it by reading out the chip), and the telescope will start slewing to the requested location on the sky.

The RRM was first offered for UVES at the *Kueyen* unit telescope in April 2004. The software, written by Ricardo Schmutzer, was set-up in such a way that it is relatively straigthforward to implement it for other instruments at the VLT. Currently this RRM is offered for the following instruments: FORS2 at *Antu*, UVES and XSHOOTER at *Kueyen*, ISAAC at *Melipal*, and SINFONI and HAWK-I at *Yepun*. In the past it was also implemented for the visitor instrument ULTRACAM. At La Silla, as mentioned before, an RRM system has also been implemented for GROND at the ESO/MPI 2.2m.

3. SCIENTIFIC RESULTS

Although the Rapid-Response Mode (RRM) can in principle be used for immediate observations of any transient event, so far it has been solely applied to the study of GRBs. The Swift satellite,[4] launched in November 2003, has been very successful in discovering a large number of GRBs, over 500 so far, providing accurate localizations within minutes of the burst. Different groups have been using these Swift alerts to trigger the VLT. Even though

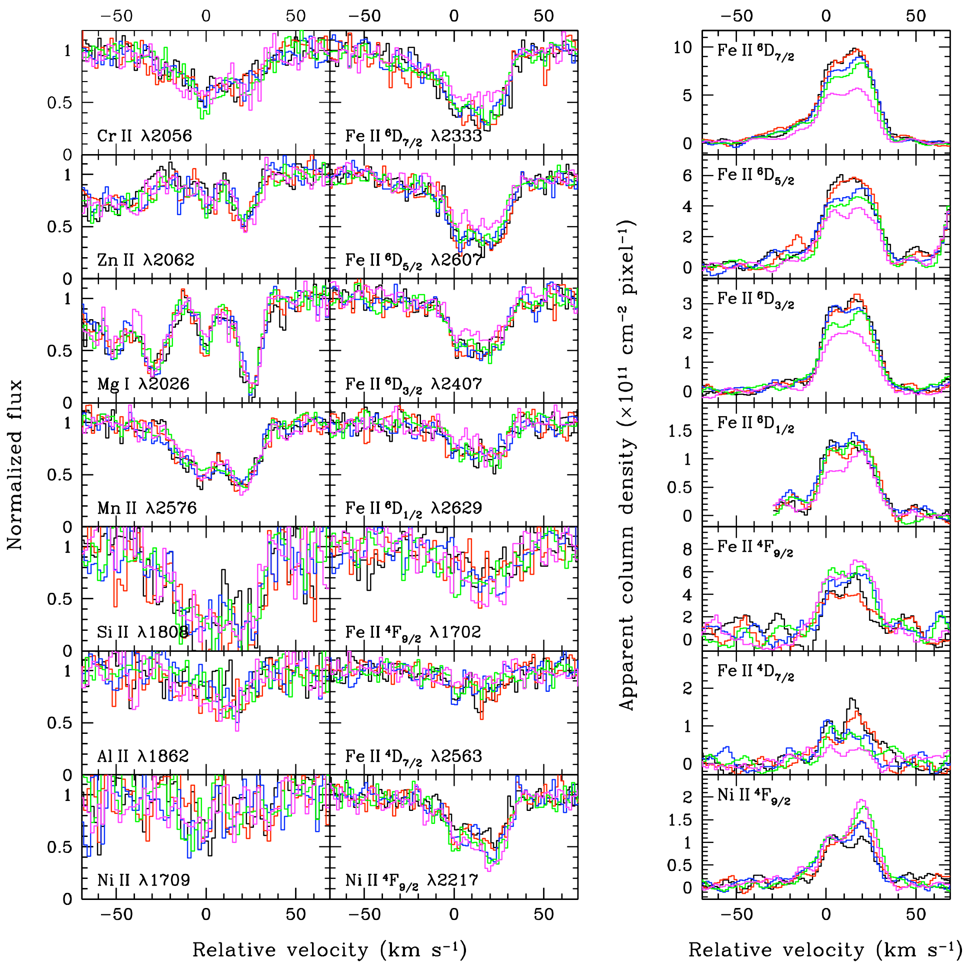

Figure 1. The epoch 1-5 UVES spectra of GRB 060418 are overplotted with the colours black, red, blue, green and magenta, respectively. In the left panel individual lines are shown, typical resonance lines on the left, and the lines arising from the excited levels of Fe II and Ni II on the right. The latter show evidence for a varying equivalent width as a function of time. To make this variability clearer, we have combined various lines that arise from the same level and constructed apparent column density profiles, smoothed with a boxcar of 5 pixels; these are shown in the right panel.

Swift discovers about a hundred bursts per year, relatively few are immediately observable from Paranal and therefore suitable for an RRM activation. The total number of successful RRM activations since April 2004 is 32, or about 5 per year, for a total time-on-target of about 46 hours. Split by instrument the number of triggers (hours on target) are as follows: FORS1: 6 (4:51), FORS2: 13 (11:43), ISAAC: 4 (1:21), and UVES: 9 (27:52). Since our team is mostly involved in UVES observations of GRB afterglows, we will focus on the results from Rapid-Response Mode in combination with UVES.

3.1 Absorption-line variability studies

Before the implementation of the RRM at the VLT, the typical time between the burst and the start of the VLT observations was of the order of 30-60 minutes. With the RRM this has decreased down to 5-10 minutes, which has made it possible to clearly detect absorpion-line varibility (except for the case of GRB 020813, where variability was observed in one absorption line at the 3-σ level[5]). All afterglows where variability has been observed were thanks to the RRM. We will now discuss several cases for which this has been observed and what we have learnt from these.

3.1.1 Time-variable absorption lines in the host galaxy of GRB 060418

On April 18 2006 at 3:06:08 UT the *Swift* Burst Alert Telescope (BAT) triggered a γ-ray burst alert,[6] providing a $3'$ error circle localization. Observations with the *Swift* X-Ray Telescope (XRT) resulted in a $5''$ position about one minute later,[7] which triggered our desktop computer to activate a VLT-RRM request for observations with the Ultra-violet and Visual Echelle Spectrograph (UVES). A series of exposures with increasing integration times (3, 5, 10, 20, and 40 minutes, respectively) was performed with a slit width of $1''$, yielding spectra covering the 330–670 nm wavelength range at a resolving power of $R = \Delta\lambda/\lambda \sim 43{,}000$, corresponding to 7 km s^{-1} full width at half maximum. These observations were followed by a 80-minutes exposure in a different instrument configuration, but with the same slit width, extending the wavelength coverage to the red up to 950 nm. Fig. 1 shows the evidence for variability of all four fine-structure levels of Fe II ($^6D_{7/2}$, $^6D_{5/2}$, $^6D_{3/2}$, and $^6D_{1/2}$), as well as from transitions from metastable levels of Fe II ($^4F_{9/2}$ and $^4D_{7/2}$) and Ni II ($^4F_{9/2}$).

The fine-structure and metastable levels can be populated through (1) collisions between the ion and other particles such as free electrons, (2) direct photo-excitation by infra-red (IR) photons (with specific wavelengths between 87-260 μm), and/or (3) indirectly through excitation by ultra-violet (UV) photons, followed by fluorescence. Detection of transitions from these energetically lower excited levels provides a powerful probe of

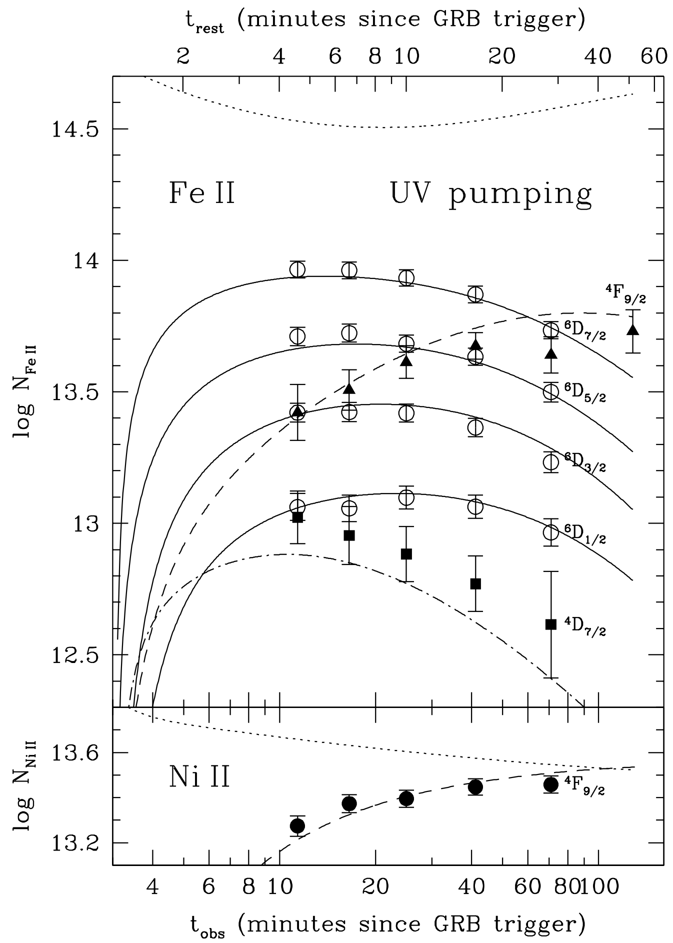

Figure 2. The column densities of Fe II (top panel) and Ni II (bottom) of various excited levels: the fine-structure levels of the ground state (data: open circles, model: solid lines), the first metastable level $^4F_{9/2}$ (Fe II data: solid triangles, Ni II data: solid circles, model: dashed line) and second metastable level $^4D_{7/2}$ (data: solid squares, model: dash-dotted line). The model prediction for the evolution of the Fe II and Ni II ground state column densities are shown by the dotted lines. All Fe II and Ni II column densities are very well described by the UV pumping model.

the physical conditions in the interstellar medium,[8] where the quantities that can be derived depend on the excitation mechanism.

We model the time evolution of the Fe II and Ni II excited levels with three different models: collisions, direct excitation by infrared photons, and indirect excitation through UV pumping. Both the collisional and direct excitation mechanisms can be discarded with high confidence; we refer the reader to Ref. 9 for the details. We here focus on the success of the UV pumping model - as shown in Fig. 2 - in which GRB UV photons excite atoms in a cloud at distance d and with initial column density N for Fe II and Ni II. The best-fit values for the fit parameters are as follows: log N(Fe II ground state)=$14.75^{+0.06}_{-0.04}$, $d = 1.7 \pm 0.2$ kpc, $\beta = -0.5^{+0.8}_{-1.0}$, $t_0 = 74^{+12}_{-11}$ s, and $b = 25 \pm 3$ km s^{-1}, and a chi-square of $\chi^2_\nu(\mathrm{UV - Fe\ II}) = 26.2/(31-5) = 1.01$. Next, we also model the evolution of the Ni II $^4\mathrm{F}_{9/2}$ level, using 17 lower and 334 higher levels of Ni II. We fix all parameters in the Ni II fit to the best-fit values of the Fe II fit, except for the Ni II ground state column density. The resulting fit is shown in the bottom panel of Fig. 2.

The large inferred distance indicates that the neutral gas detected in the spectrum of GRB 060418 is not in the immediate vicinity of the GRB itself, as previously expected. Since this observation, GRB-absorption gas distances have been inferred using the same modelling technique for a few other GRBs: 050730,[10] 080319B,[11] and 080330,[12] and the inferred distances range from 300 pc to 6 kpc away from the GRB. These distances are surprisingly large, but consistent with other studies that have inferred that the minimum distance of the neutral material from the GRB is at least 50-100 pc.[13,14]

3.1.2 Excitation and ionization by GRB 080310

GRB 080310, again discovered by *Swift*,[16] provided another opportunity for a VLT RRM activation with UVES, with the start of the first spectrum at 13 min. after the GRB trigger. The Paranal staff was able to complete four spectra with different settings with increasing exposure times before the morning twilight set in two hours later; this resulted in two epochs covering the entire optical spectral range, with a resolution of about 7 km s^{-1}.

The UVES spectra of GRB 080310 are unique as they reveal absorption lines of an excited level of FeIII, which have never been observed before in a GRB afterglow. The Fe III UV 34 triplet at $\lambda\lambda$1895,1914,1926, arising from the exited electronic configuration $^7S_3$, was previously observed in extreme environments such as ηCarinae[17] and BAL Quasars.[18] The populations of both FeII and FeIII are varying in time, as can be seen in Fig. 3, suggestive of ionization of Fe II atoms by the GRB afterglow. We have included ionization in our photo-excitation code, and the best fit (so far, this is still work in progress) is shown by the solid lines in Fig. 3. The best-fit distance that we obtain is several tens of parsec, which is much closer in than found for other GRBs. But the short distance is not the only reason why these excited levels of Fe III are detected: a low hydrogen column density is required as well. If the GRB 080310 sightline would have had the H I column density typically observed for GRB host galaxies, of the order of log N(HI) of 21-22, the hydrogen would have screened the absorption cloud from FeII ionization taking place. This observation of GRB 080310 shows that in some cases the immediate surroundings of a GRB explosion can be probed with optical/near-IR spectroscopy, providing insight into the star-forming region in which the GRB progenitor was born.

4. THE RRM FUTURE

The RRM software has been programmed in a general way in the VLT software environment, and can therefore be easily implemented for any new instrument joining the VLT, including possible visitor instruments (in the past the RRM has been successfully used in combination with the ULTRACAM visitor instrument). X-shooter is the first of the 2nd generation of instruments at the VLT. It is a medium resolution spectrograph that covers the UV-optical-near-IR spectral range (0.3-2.5 μm) in a single exposure. This makes it the ideal instrument to chase GRB afterglows as their redshift is not known beforehand. In principle, X-shooter is able to observe GRBs from any redshift up to about 17, should they exist at such an early stage.

A GRB afterglow program, led by the X-shooter Guaranteed Time Observations (GTO) team with Johan Fynbo as the PI, has started observing carefully-selected GRB locations with X-shooter last October. The RRM has also been implemented for X-shooter. Although the ToO part of the program is producing regular redshifts and metallicity measurements, the main goal of the program, the RRM part has been less fortunate so far. So

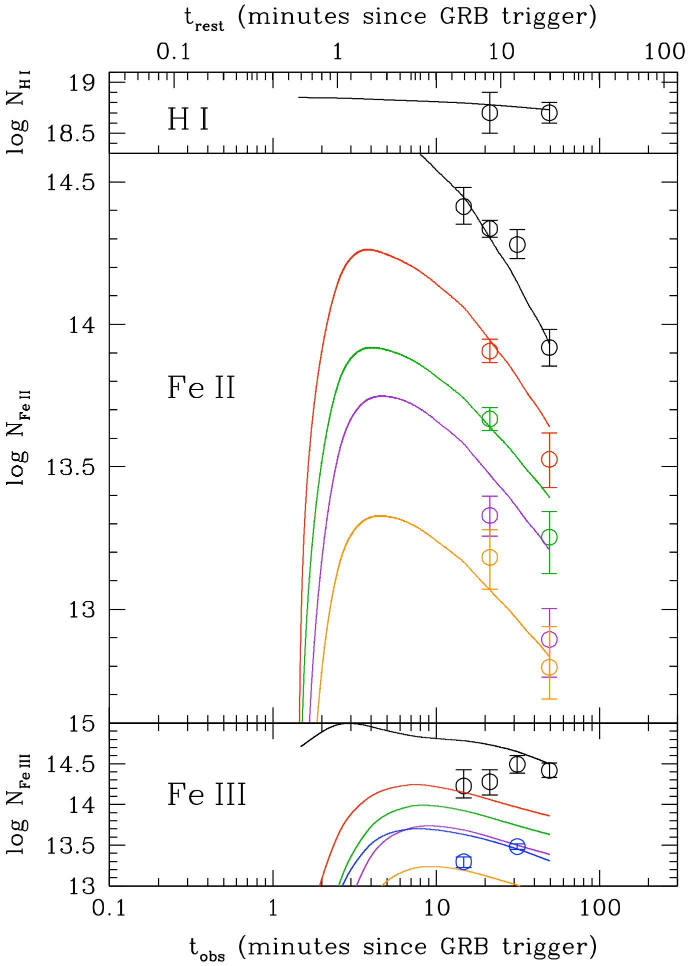

Figure 3. Column density evolution of neutral hydrogen (top panel), ground state and excited levels of Fe II (middle) and Fe III (bottom). The column density of a metastable level of Fe III ($^7S_3$, bottom panel) - never seen before in GRB afterglows - is increasing with time, while Fe II is decreasing, suggesting that Fe II is being ionized to Fe III. Modelling of both photo-excitation and photo-ionization is quite successful at describing the evolution of Fe II, but for Fe III it does not provide a good fit. Although this is still work in progress, the best-fit distance of the absorption cloud to the GRB is of the order of 50 pc, much closer in than inferred for other GRBs.[15]

far four activations have been sent; 3 out of 4 times the telescopes were closed, or soon had to close, due to bad weather, and once the focus was set to UVES at the *Kueyen* unit telescope, and so X-shooter could not be triggered in RRM. However, when the RRM will be triggered successfully, it will lead to very high quality X-shooter spectra. The probability of a very high redshift burst that is immediately observable from Paranal is not very high, but if it does occur, the RRM will be instrumental in boosting the spectral signal-to-noise to allow inference of various quantities such as metallicity and neutral gas fraction surrounding the reionization-epoch GRB.

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