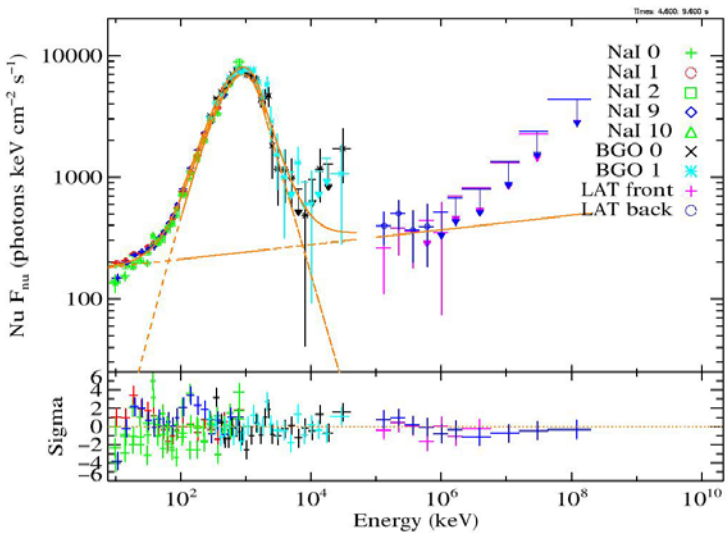
Gamma-Ray Bursts – The Phenomenon and a Tool

The understanding of gamma-ray bursts (GRBs) has dramatically increased over the last 3 years, primarily due the combination of successful continuation of the NASA Swift mission and ground-based follow-up observations, and the launch of NASA's Fermi satellite in June 2008. At the same time, the application of GRBs as probes of the early Universe has made dramatic progress. While the use of GRBs to study the properties of their host galaxies is discussed in the section on galaxy evolution, here we describe the recent contributions of MPE's GRB group to the study of the prompt and afterglow emission properties.

The physics of the prompt emission in GRBs is still widely debated. While there is general agreement on a non-thermal origin, and mathematically the spectra are well fit by the empirical Band function (two smoothly joined power laws) or a cut-off power law, two problems plague theoreticians: first, the slope of the low-energy power law of the Band function does not obey the synchrotron limit. Second, the higher the photon energy that is measured, the higher is the required Lorentz factor to avoid the compactness problem, i.e. the pair creation threshold in the dense photon field. Observations with the GBM (where MPE is co-PI institute) and LAT instruments on Fermi, which together span an impressive and unparalleled 7 orders of magnitudes in photon energy, were expected to solve these issues. However, the problem may have become worse with the discovery of the long-duration GRB 090902B: it was one of the brightest GRBs observed by the LAT, which detected several hundred photons above 100 MeV during the prompt phase. Time-resolved spectral analysis revealed a significant power-law component underlying the canonical Band component and dominating the emission below ~50 keV and above 100 MeV (Fig. 1). The Band component underwent substantial spectral evolution over the duration of the burst, while the photon index of the power-law component remained constant for most of the prompt phase, and then hardened significantly toward the end. Not only is the origin of this separate power law component difficult to explain, but more generally this implies much larger energies emitted in the GeV band. The highest energy photon measured (33 GeV) from this burst (in fact from any GRB so far) at a redshift of 1.82 implies a minimum Lorentz factor of >1500 (under the synchrotron origin assumption); this can be relaxed in the synchrotron-self-Compton scenario which is therefore favoured (Abdo et al 2009, ApJ 706, L138; contact authors Bissaldi & McBreen).



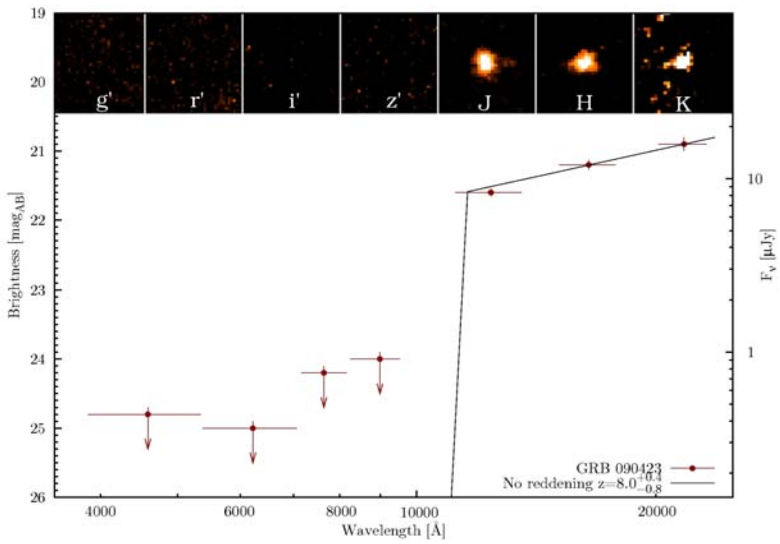
Besides GRB 090902B, several more LAT-detected events are among the most energetic (equivalent isotropic energy emitted) bursts ever observed. Observations of the afterglows of some of these bursts with GROND have allowed us to measure the jet opening angles, and thus to go even one step further: it turns out that also the true, beaming-corrected energy release is very high (McBreen et al 2010, A&A in press; Rau et al. 2010, ApJ subm.). In fact, for several of these bursts this energy is approaching the maximum rotational energy of a proto-neutron star indicating that the remnant must be a black hole and not a millisecond magnetar.

Another intriguing observational result from Fermi-LAT is the detection in nearly all GRBs of GeV emission which lasts for about one hour after the trigger. Again, the nature of this emission is under debate, with inverse Compton being the prime suspect for the emission mechanism.

The afterglow emission of GRBs is now largely understood thanks to the enormous achievements of the Swift mission by both making unique measurements predominantly in X-rays as well as enabling ground-based follow-up observations through the rapid dissemination of accurate GRB positions. GROND, the 7-channel imager built at MPE and operated at the 2.2m MPI telescope at ESO/Chile since mid-2007, is one of the instruments that exploits the Swift positions. The strategy of following each observable Swift burst for as long as possible has allowed us to discover surprising optical flaring activity on top of the canonical afterglow decay (e.g. Greiner et al. 2009, ApJ 693, 1912). One particularly rewarding case was the burst 071031: The densely sampled early light curve (between 4 min and 7 hrs after the trigger) of the optical/near-infrared (NIR) afterglow consists of 547 individual data points and shows several flares which are superimposed onto the overall rise and decay of the afterglow. These flares have also been seen with the Swift X-ray telescope. We find evidence of spectral hardening in the optical/NIR bands contemporaneous with the emergence of the bumps from the underlying afterglow component. The extrapolation of these hard SEDs matches nicely the X-ray spectra (which actually soften during the flares), and can be consistently described as a continuous shift of the peak energy from the X-ray to the optical band. This and the timing properties suggest late central engine activity as the common origin of these flares (Krühler et al. 2009, ApJ 697, 758).

Another example of the benefit of extended, simultaneous multi-band imaging is the possibility to **constrain the jet geometry** in the bursts 080413B and 080710: in both cases it was possible to develop a relatively simple model which fits both the GROND as well as the Swift X-ray data. The subtle changes in decay slope and correlated spectral changes lead pretty uniquely to a two-jet scenario (080413B; Filgas et al. 2010, subm.) and an off-axis viewing angle (080710; Krühler et al. 2010, A&A 508, 593), respectively.

Star formation and chemical evolution in the Early Universe are the main areas where GRBs are particularly useful as tools. The gamma- and X-ray emission is used to pinpoint the locations of high-redshift objects, and the bright optical/NIR afterglow emission is then used to study the physical conditions in the burst environment as well as along the line-of-sight. Since the launch of Swift in 2004, the GRB redshift frontier has been continuously pushed. A nice demonstration of the working principle of GROND to quickly identify high-redshift GRBs was the detection of the afterglow of GRB 080913 and the recognition of its high-z nature via the detection of a spectral break between its i'- and z'-bands (Greiner et al. 2009, ApJ 693, 1610). Spectroscopic observations with the VLT were triggered by us within ~90 min after the burst, confirmed the high redshift (6.69) and made GRB 080913 the highest redshift GRB at that time, and more distant than the highest-redshift QSO.



Only seven months later, after initial indications of a very high redshift by a British/American group, GROND provided the first reliable redshift-estimate ($8.0^{+0.4}_{-0.8}$) for GRB 090423 (Fig. 2) which subsequently was confirmed by spectroscopic measurements with larger telescopes (z=8.2, Tanvir et al. 2009, Nat. 461, 1254). GRB 090423 is not only the highest-redshift object known to date (at the time of writing), but also demonstrates that massive stars were being produced and died as GRBs only 630 Myr after the Big Bang.