REPORTS FROM OBSERVERS

Gamma-Ray Bursts[1] – Pushing Limits with the VLT

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1. Introduction

"New kids on the block" – perhaps this is the best way to describe cosmic gamma-ray bursts among the multitude of object types that can be studied by optical telescopes. When they pop up, they give a lot of trouble, and for a while take the attention from all the work in progress. In this report we will describe how ESO observers are making most out of these exciting opportunities, and how the VLT promises to integrate space and ground-based observations in a way never achieved before. But first a few words on the historical background.

2. The Basics

Cosmic gamma-ray bursts (GRB) are studied from spacecraft, since γ-radiation does not penetrate the Earth's atmosphere. The first detection was made in 1967, but the phenomenon became publicly known only in 1973, when 16 events were published, in the *Astrophysical Journal*. This first paper led to a flurry of theoretical works; for several years, the rate with which models were proposed kept pace with the detection of new events. Likewise, on the experimental side, numerous initiatives were taken. To date, more than 60 spacecraft have carried successful gamma-ray burst detectors. The most efficient was BATSE on board the Compton Gamma-Ray Observatory. This instrument has detected about one event every day, on average, since its launch in April 1991.

The hallmark of gamma-ray bursts is diversity: durations can be anything between a few milliseconds and several minutes. Gamma-ray burst 'light-curves' take numerous shapes, from smooth, single peaks to very jagged, multi-peaked graphs. They come from ever new directions, and until recently they could not be associated with any known object population, be it solar-system objects, stars from the Milky Way, distant galaxies, or even quasars. Their γ-ray spectra do not show any obvious emission or absorption lines that could help identify the physical processes responsible for the phenomenon.

Many gamma-ray bursts are surprisingly bright (in γ-rays, 0.1–100 MeV) – for a short moment they easily outshine the sum of all other celestial high-energy sources. Conversely, near the instrumental detection limit there are fewer events than expected from a homogeneous distribution through an Euclidean space. This lack of faint bursts could be explained by either a large Galactic halo population, or a cosmological origin for gamma-ray bursts.

During the early years, it was repeated over and over that optical observations were needed to finally clinch the distance question. Only thereby could one know the total (absolute) amount of energy emitted, and then start discussing in earnest, what is the fundamental physical process in gamma-ray bursts.

3. The BeppoSAX Legacy

In the beginning of 1997, this wish was fulfilled. The previous year, an Italian-Dutch consortium had launched the *Satellite per Astronomia X*, SAX, nicknamed BeppoSAX after the Italian Cosmic-ray and X-ray astronomy pioneer Giuseppe Occhialini.

The satellite was primarily intended to study the 0.1–300 keV spectrum of galactic and extragalactic sources with four Narrow-Field Instruments (NFIs). The scientific payload onboard BeppoSAX also includes a Gamma-Ray Burst Monitor (GRBM, 40–700 keV, all-sky coverage), which is the non-imaging anticoincidence system of the high-energy NFI (the PDS), and two coded-mask Wide-Field Cameras (WFCs, 2–26 keV, 40° × 40° field), pointing at right angles with respect to the NFIs.

Although gamma-ray burst investigation was a secondary task of BeppoSAX, the simultaneous detection of gamma-ray bursts by the GRBM and one of the WFCs proved to be crucial in identification of their counterparts at lower energies thanks to the rapid (4–5 hours) and accurate (~ 3′) localisation afforded by the WFCs.

The good scheduling flexibility of BeppoSAX allows a prompt repointing of the NFIs at the gamma-ray burst error circle and efficient search of the X-ray counterpart. In case of NFI detection of a gamma-ray burst afterglow candidate in X-rays, the error circle is reduced to ~ 50″ in radius. Meanwhile, the rapid dissemination of the error circle centroid co-ordinates makes fast follow-up at ground-based telescopes possible.

The first error circle thus established was for GRB 960720, but came 45 days after trigger and did not result in the finding of a counterpart (in 't Zand et al., 1997). The next, GRB 970111, was announced promptly, and search in the initially large WFC error circle turned up a number of sources, none of which lay in the refined error circle established a few days later[2]. Then, 'third time lucky', came the burst of 28 February 1997, which revolutionised the field. It was detected in the WFC and located to a 3′ error circle. Prompt reorientation of the satellite and activation of the NFIs 10 hours after the burst led to the localisation of a bright, previously unknown X-ray source (Costa et al., 1997).

A second NFI observation 3 days later showed that the source had faded by a factor of 20. Subsequent observations with the ASCA and ROSAT satellites confirmed that the source faded with a power-law, $I \quad (t - t_{\mathrm{GRB}})^{\alpha}$ where time is counted in days, and $\alpha \sim -1.3$. This type of decay had indeed been predicted by Mészáros and Rees (1997). In their "fireball" model, a mixture of matter and photons expands at

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[1] This year's *Annual Review of Astronomy and Astrophysics* will include a review paper on Gamma-Ray Bursts, authored by Jan van Paradijs, Chryssa Kouveliotou, and Ralph Wijers.

[2] In hindsight, the NFI follow-up observation of this event shows a faint source. This source is consistent with being an afterglow, given what we have learnt of afterglows from later events, but was not recognised as such at the time.

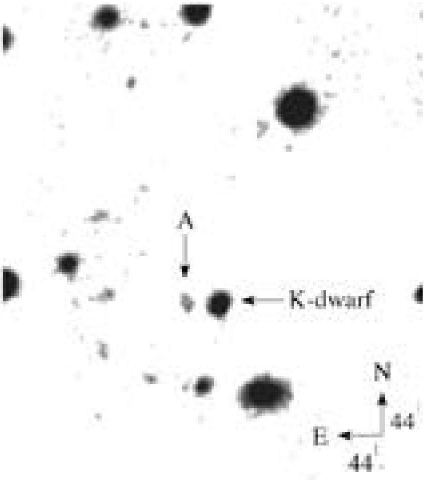

Figure 1: The first optically identified gamma-ray burst, GRB 970228. This image, obtained at the NTT on March 13, 1997, gave the earliest indication that the source was located in a remote galaxy (van Paradijs et al., 1997). "A" marks the combined light of the optical transient and candidate host galaxy, later verified by Hubble Space Telescope observations.

high speed and makes the interstellar medium radiate synchrotron emission when it impacts on it; thus it is exactly like a supernova remnant, except relativistic speeds are involved.

4. The First Optical Transient

The initial 3′ localisation from BeppoSAX's WFC allowed independent ground-based optical observations to start 20.8 hours after the gamma-ray burst. The late Jan van Paradijs, and his two students, Titus Galama and Paul Groot, took this opportunity to make the observation, which forever changed gamma-ray burst astronomy. An exposure from the William Herschel Telescope showed a 21st magnitude object, which had faded by more than 2 magnitudes, when the observation was repeated some days later. Subsequent ESO NTT observations (March 13) showed a fuzzy object at the place where the optical transient (OT) had been (Fig. 1); this was interpreted as a host galaxy (van Paradijs et al., 1997).

This first detection of an optical transient (optical afterglow) sparked an international observing effort, which was unique, except perhaps for SN 1987A. All major ground-based telescopes were used, optical as well as radio. The fading of the optical transient became well documented over a wide wavelength range (Figs. 2a and 2b), and the Hubble Space Telescope confirmed the existence of a host galaxy, which indeed is small and not very conspicuous. The host's distance could not be gauged from the pictures, and remained unknown until 1999, when Keck-II observations placed it at $z = 0.7$ (Djorgovski et al., 1999). At that distance, a supernova would have peaked at magnitude R ~ 25.2; i.e. about 50 times fainter than observed for the OT.

5. A Treasure Hunt of Sorts

It had thus become obvious, that ground-based observers can harvest beautiful and important results, by maintaining close links to the space community.

In this way, observations can start within hours from a gamma-ray burst, perhaps even faster, hence raising the expectation that a counterpart will be encountered brighter than the 21st magnitude found for GRB 970228. Such *targets of opportunity* are now pursued with high priority at many observatories, including La Silla, Paranal and the Hubble Space Telescope.

Key to this process is the distribution via internet of positions derived from SAX, RXTE and from the Interplanetary Network, IPN, (consisting of Ulysses and NEAR, in addition to near-Earth detectors like BATSE, SAX, and Wind). This service is operated by Goddard Space Flight Center (NASA) and has more than 400 clients.[3]

By the time this article goes to press, some 18 low-energy (optical, infrared, radio) counterparts have been identified, worldwide.[4] In a similar but larger number of cases, no optical counterpart

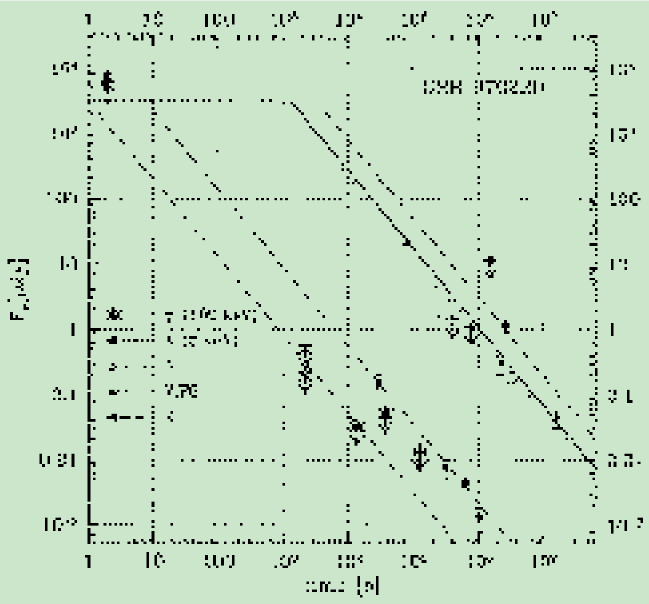

Figure 2a: The afterglow of GRB 970228. The decay of the afterglow emission, over a wide range of energies is shown from γ-rays to the near infrared (K-band). Time is measured in seconds, following the moment of the gamma-ray burst, 1997 February 28.1236 UT. The lines indicate the power-law prediction for a specific blast wave model (from Wijers, Rees, and Mészáros, 1997, with recent data added).

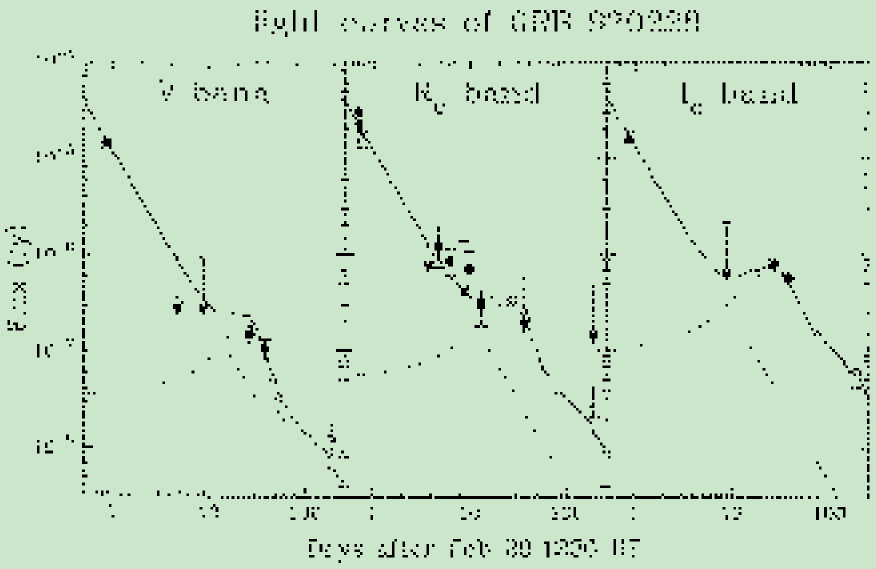

Figure 2b: The light curve of the very first optical transient, OT/GRB 970228, discovered by Jan van Paradijs. The photometric development is documented in three colours, V, R and I. The loss of brightness had already started when optical observations began almost one day after the gamma-ray burst. A hump in the light curve may be caused by a supernova-like component (Galama et al. 2000).

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[3] http://gcn.gsfc.nasa.gov

[4] For details, see Jochen Greiner's site http://www.aip.de/~jcg/grb.html The present collaboration plans to establish a web site with information on its activities and results; the URLwill be provided later.

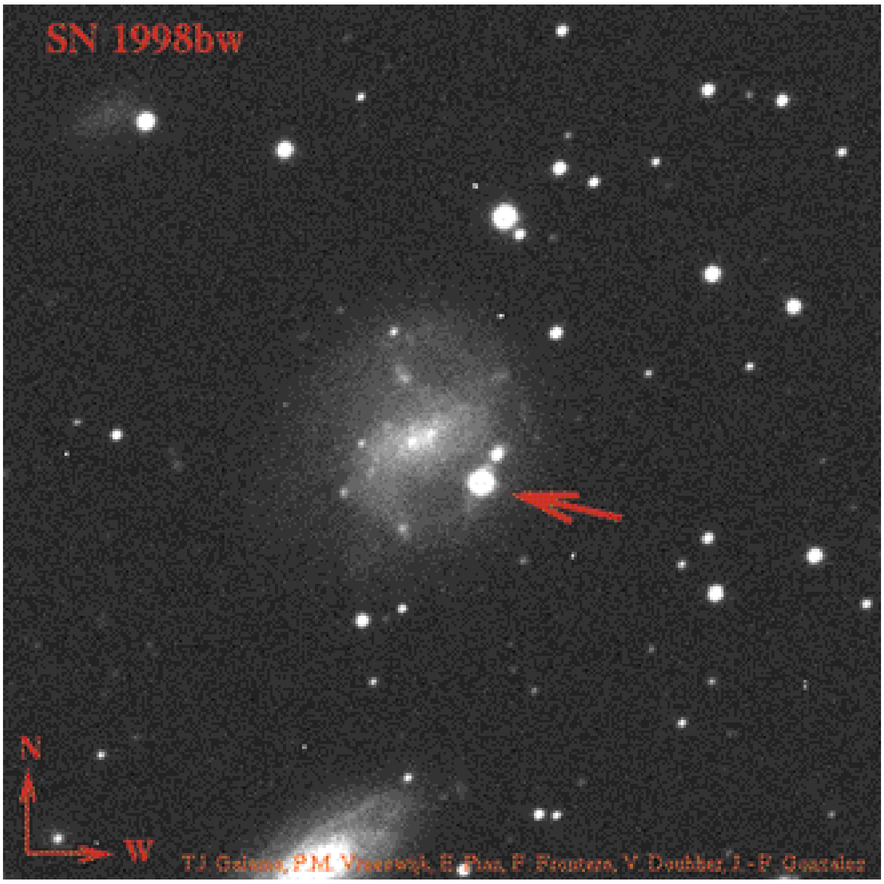

Figure 3: On April 25, 1998, a gamma-ray burst appeared from a location compatible with a highly unusual supernova, SN 1998bw, in the spiral galaxy ESO 184-G82. This picture was obtained at the NTT on May 1, 1998 (Galama et al., 1998). If the association is physical, this implies a much closer distance than observed for several other gamma-ray bursts.

was found. The reason for this is not clear; possibly these searches were not swift nor deep enough, but in two cases (GRB 970828, 000214, and perhaps also 970111) the optical fluxes, predicted from X-ray observations are well above detection limits.

The high redshift found for the GRB 970228 host galaxy turned out not to be anywhere near the record. For GRB 971214, the value z = 3.4 was found (Kulkarni et al., 1998), implying that the burst was emitted 10 billion years ago, equivalent to when the Universe was 11% of its current age.[5] The energetics are equally stunning: assuming isotropic γ-ray emission, this burst must have emitted 3×10^{53} erg, equivalent to 16% of the Sun's rest-mass energy.

6. The Supernova Connection

Just as redshifts in the range 0.7–3.4 were about to become accepted, a gamma-ray burst from April 25, 1998, gave reason to rethink the distance scale. The gamma-ray burst itself was not exceptional, but the optical counterpart certainly was. Observations initiated three days later, at the NTT, showed that the error box included a catalogued galaxy, ESO 184–G82. In one of the spiral arms, a 16th magnitude object was noted (Fig. 3); spectroscopy showed this to be a supernova, of type Ic. Could this be a chance alignment? Taking into account the coincidence in both time and place, Jan van Paradijs conservatively calculated the probability as 10^{-4}. This is small, but not entirely convincing. The distance to the galaxy was quickly measured with the Anglo-Australian Telescope to be z = 0.0085, or a mere 130 million light-years. If really the high-energy event was that close, it would mean that gamma-ray bursts span over a very wide, intrinsic luminosity range, at least a factor 10,000 (Galama et al., 1998). Adding to the probability that the two phenomena are indeed related, is the fact that the SN 1998bw in itself is highly unusual, with outflow velocities exceeding 50% of the speed of light (e.g. Leibundgut et al., 2000).

Could there be other supernovae, emitting gamma-ray bursts, or could a SN-like contribution to the light-curve be detected in other optical transients? Naturally, the existing material was scrutinised, and for OT/GRB 970228, the very first OT, a hump, consistent with a high-redshift supernova is indeed noted some 20–30 days after the gamma-ray burst (Fig. 2). Also for GRB 980326, a SN-hump was found (Bloom et al., 1999). In other cases no such SN signature has been observed. It remains uncertain, if there are several classes of cosmological gamma-ray bursts or if all are associated with supernovae, or none.

7. A Spectacular Event in the Northern Sky

On January 23, 1999, a very bright gamma-ray burst occurred in the Northern sky. Its approximate position, derived from BATSE, was distributed over the internet, and within seconds, a robotic telescope at Los Alamos National Laboratories started taking pictures. It caused a sensation in the GRB community, when these data were examined: in its maximum, 47 seconds after the burst trigger and before the γ-ray emission had ceased, the OT had been as bright as 9th magnitude (Akerlof et al., 1999); it could, in principle, have been seen in a pair of binoculars!

The first expectation was that this event was very close. However, a few days later, the redshift z = 1.6 was derived (from Keck-II and the Nordic Optical Telescope). This implies an energy output corresponding to almost two neutron star rest masses. Or in other terms: if GRB 990123 had taken place in the Andromeda Galaxy, the optical flash would have been as bright as the full moon! Such energy output challenges some of the most popular models for the basic energy source, merging pairs of neutron stars. It should also be recalled that no known stellar process will convert mass to electromagnetic energy with 100% efficiency, much is lost in neutrinos. However, if the outflow was directional or jet-like, instead of isotropic, this 'energy crisis' could be lifted.

Unfortunately, it is not the rule that all OTs reach this peak brightness. In at least a dozen of other cases a limit of 14th magnitude was found from robotic CCD observations, and less stringent limits exist from wide-field (all-sky) photographic exposures.

8. Discovery of Polarisation

With the first unit of the VLT (ANTU) in service in April 1999, it was natural to do an all-out effort, as soon as a suitable event occurred. On May 10, members of our team identified the counterpart of a gamma-ray burst, using the Sutherland 1-m in South Africa. When it became night in Chile, everything was prepared, and FORS1 data could be taken already 20 hours after the gamma-ray burst.

This gave one of the first opportunities to try polarimetric observations of a gamma-ray burst counterpart. The splitting of light in orthogonal planes has the potential of revealing information on the

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[5] For standard cosmology parameters H_0 = 65 km/s/Mpc, Ω = 0.3, Λ = 0.

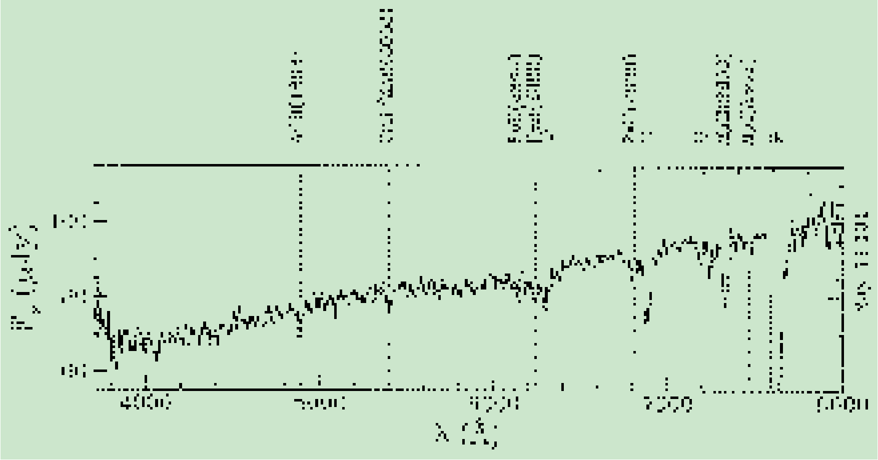

Figure 4: A VLT/FORS1 spectrum of the afterglow of ORB 990510, 20 hours after the burst. Several absorption features are detected, corresponding to the redshift z = 1.6; the OT and the host galaxy may well be more distant. Special symbols mark telluric (atmospheric) absorption bands. Adapted from Vreeswijk et al. (1999b).

nature of the light source. The VLT data showed a significant amount of linear polarisation, 1.6 ± 0.2 per cent, 0.86 days after the burst, and similar, after 1.81 days (Covino et al., 1999; Wijers et al., 1999). It was concluded that the polarisation is intrinsic to the source and that it supports the emission's origin as synchrotron radiation. Polarisation, especially a change in polarisation degree and angle, can also argue for a jet-shaped outflow. The second polarisation measurement, although of lower significance, indeed provides this evidence (see also below). It is clear, though, that this research is in its infancy.[6]

Optical spectra at several epochs were also obtained, displaying several metal absorption lines from e.g. ionised iron, neutral and ionised magnesium. This implies that the OT was at a redshift of $z > 1.6$ (Fig. 4). The neutral magnesium is indicative of a low-ionisation, dense interstellar medium, most likely that of the host galaxy. However, neither the VLT nor Hubble was able to detect a galaxy at the position of the optical afterglow down to V ~ 28. This shows the enormous power of gamma-ray bursts to probe the interstellar medium to high redshifts. The spectral flux distribution and the light curve support the interpretation of the afterglow as synchrotron emission from a jet (Covino et al., 1999; Wijers et al., 1999).

9. NTT and VLT Setting Standards

With less than 20 OTs known, almost any new discovery will strike a record of some kind. In case of GRB 990712, the VLTspectrum gave the redshift z = 0.43, corresponding to 4 billion years (Vreeswijk et al. 1999b; Hjorth et al. 2000). This is larger than found for the presumed association GRB 980425 / SN1988bw, but smaller than other OTs, for which the median redshift is near z = 1.

The faintest OT at discovery was OT/GRB 980329, measured at R = 23.6 when first detected at the NTT (Palazzi et al., 1999).

Another remarkable NTT discovery was that of OT/GRB 990705; this was the first identification achieved in the near-infrared (Masetti et al., 2000).

Optical spectroscopy of GRB 991216 gave the first indication of multiple absorption line systems, conceivably arising from clouds separate from a host galaxy, and much closer to the Earth. The particular observation was made at the VLT, and showed no less than three absorption line systems, at z = 0.77, z = 0.80 and z = 1.02 (Vreeswijk et al., 1999a). The redshift of the OT must then be $z \geq 1.02$

A record of sorts was due to a gamma-ray burst from January 31, 2000, positioned by means of IPN data; this became the OT identified with the longest delay. When VLT observations could begin, on February 4, it was already more than three days since the burst, and hopes for an optical identification were not high, in particular, since the error box was larger than the FORS1 field of view. Taking two pointings, and repeating them two and four days later, the OT was discovered as a red, fading object, $R > 23$ (Fig. 5) (Pedersen et al., 2000; Andersen et al., 2000).

10. GRB 000301c – a Multi-Site Event

The study of gamma-ray bursts has become a field where contributions from many sites are needed, partly for around-the-clock coverage, partly for wavelength coverage. Observations typically start with a space-borne detection, followed by ground-based optical, infrared, and radio studies.

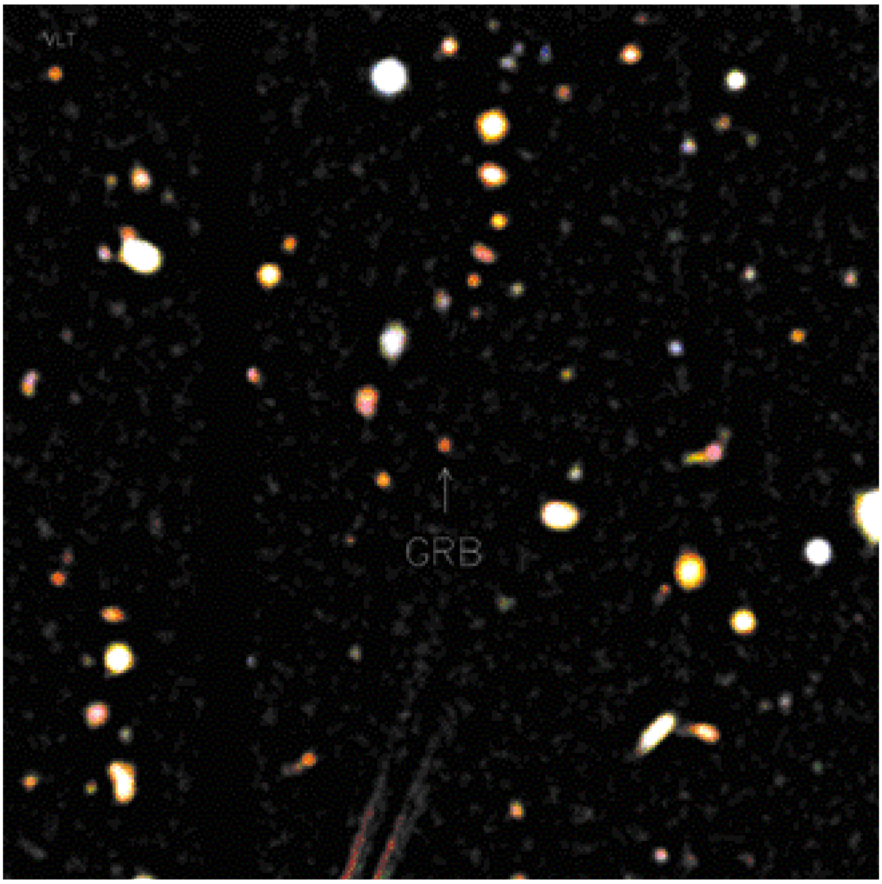

Figure 5: A true colour photograph of GRB 000131, obtained from VLT/FORS1 and 1.54-m Danish observations. From Andersen et al. (2000).

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[6] A second, successful polarisation measurement was made on GRB 990712 (Rol et al., *ApJ*, submitted).

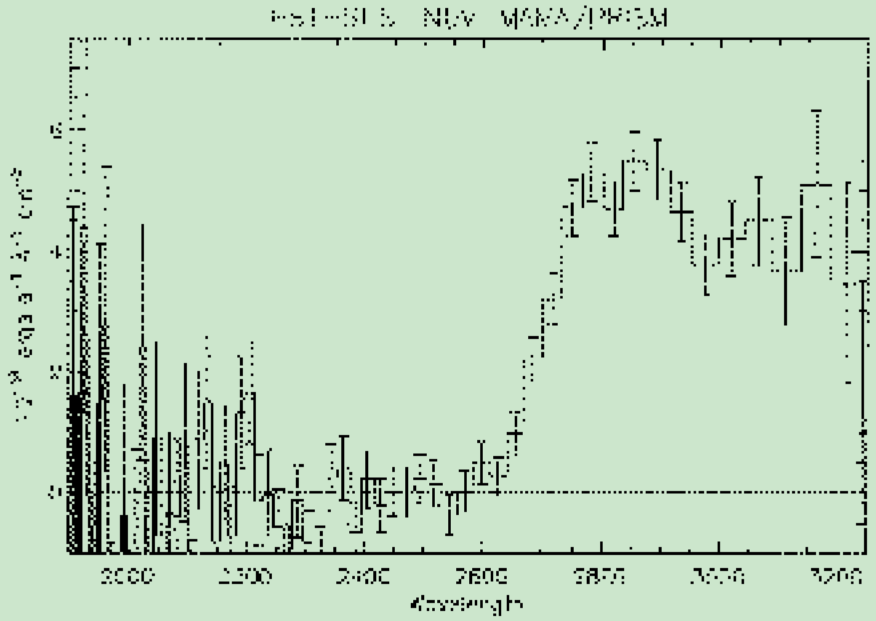

Figure 6: In this spectrum of OT/GRB 000301c, obtained with Hubble Space Telescope 33 days after the outburst, no light is detected below λ = 2600 Å. This has been modelled in terms of redshifted Hydrogen (Lyman edge) absorption, putting the source at z ~ 2 (Fruchter et al., 2000a,b). With kind permission from the STSci GRB team.

GRB 000301c may serve as an illustration. This was a brief (~ 10 s) event, localised by means of data from RXTE, NEAR and Ulysses. The first to react were two Indian observatories, and telescopes at Loiano, Calar Alto and La Palma (NOT). Data from the NOT provided a candidate OT, and confirmation was soon received from elsewhere, including radio-, mm and near-infrared telescopes.

Although the source faded quickly, the VLT could be used to obtain spectra, and other ESO telescopes to acquire multicolour optical photometry (Jensen et al., 2000).

The source has been subject to several runs at the Hubble Space Telescope. This included a remarkable spectroscopic observation with STIS: the Ly-α break was detected at *z* ~ 2 (Fig. 6) (Fruchter et al., 2000a). This was soon confirmed (and improved upon) with data from Keck-II (Castro et al., 2000) and VLT. Locating the host galaxy, and finding the relative position of the OT within it, turned out to be particularly difficult. Continued imaging by Hubble has failed to show clear evidence for a host, to very deep limits (Fruchter et al., 2000b).

11. Challenging Physics

The pace of discoveries in the field of gamma-ray bursts is truly remarkable. While credit for this goes to many colleagues from the space research community, we wish here to point to the people behind the BeppoSAX satellite, and in particular to Jan van Paradijs. Without his faith in co-ordinated optical observations, we would not have come nearly as far.

Current research falls in two main categories:

- the study of the origin and physical mechanism of gamma-ray bursts and
- the use of gamma-ray bursts as cosmological probes, irrespective of the underlying physical mechanism.

This is indeed what we have in mind for the next two years, during which an approved ‘Large Programme’ will be conducted. The project includes a study of the preferred locations of the bursts within the host galaxies (central location, in spiral arm, etc.) and also the very nature of the hosts. How do the typical hosts relate to other members of the high-*z* ‘zoo’, such as Lyman-break galaxies, Damped Lyman-α Absorbers (DLAs), and the luminous IR galaxies? What is the star-formation rate in these hosts?

The central questions regarding the emission mechanism involves identifying:

- the gamma-ray burst progenitors, the main contenders being merging neutron stars or collapsing massive stars (‘collapsars’),
- the emission mechanism, e.g. synchrotron emission,
- the emission geometry, in particular to what extent gamma-ray bursts are collimated and the size of the jet opening angle,
- the density structure and composition of the immediate surroundings of the gamma-ray burst.

There are high hopes that gamma-ray burst afterglows will prove useful in probing hotly debated cosmological questions, such as the large-scale structure of the Universe, the star-formation history of the Universe, the very high-redshift Universe, the effect of extinction at high redshifts, and the nature of DLAs. Gamma-ray bursts could well be among the most distant detectable sources in the Universe; if they come from massive stars they should occur soon after the first stars formed, perhaps at redshifts as high as *z* ~ 20. With this in mind, future searches at ESO will apply the VLT’s ISAAC and NTT’s SOFI, in addition to optical instruments.

Our programme also aims to improve on typical response times, so that UVES observations can be conducted in a semi-automated fashion, while the OTs are sufficiently bright, perhaps within 5 minutes from the ‘trigger’ moment delivered by spacecraft. This may reveal knowledge not only about the OTs and their hosts, but also about the intervening intergalactic medium; in this way, OTs may turn out to be more useful cosmological probes than quasars.

The unpredictable nature of gamma-ray bursts implies that the programme can only be executed under *target-of-opportunity* conditions. We appreciate the kind assistance rendered by ESO staff, and the understanding shown by many regularly scheduled observers, who got bumped.

Within the next few years, several gamma-ray-burst detecting satellites will be launched. First among these are the US/France/Japan mission HETE-2 scheduled for launch later this year; it is expected to provide at least 24 events annually, accurate to 10 arcsec – 10 arcmin. Later come the ESA mission INTEGRAL (launch 2002; ~ 20 events per year), the US/UK/Italy Swift (2003; ~ 100 events per year to arcsecond accuracy), and the Danish Rømer mission, (launch 2003; ~ 70 events per year). All will transmit their data in real-time, over the Internet. The rate of swiftly and precisely located gamma-ray bursts will then increase dramatically. Conducting the necessary ground-based observations in *service mode* will then be the only approach to do basic research in this new and energetic field.

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ISAAC on the VLT Investigates the Nature of the High-Redshift Sources of the Cosmic Infrared Background

Two jewels of European astronomy, ISO and ISAAC, join their capabilities to shed light on one important enigma of present-day cosmology

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Abstract

We report on the status of our long-term project aimed at characterising the nature of a new population of galaxies that has emerged from various ISO-CAM surveys[1]. In September 1999, we used ISAAC on UT1 and under very good seeing conditions over two nights we obtained the first near-infrared spectra for a sample of ISOCAM galaxies drawn from a deep ISO survey of the Hubble Deep Field South. The Hα emission line was detected in 11 out of the 12 galaxies we looked at, down to a flux limit of 7×10^{-17} erg cm^{-2} s^{-1}, corresponding to a line luminosity of 10^{41} erg s^{-1} at $z = 0.6$ (for an $H_0 = 50$ and $\Omega = 0.3$ cosmology). The rest frame R-band spectra of the ISOCAM galaxies we observed resemble those of powerful dust-enshrouded starbursts. The sample galaxies are part of a new population of optically faint, but infrared luminous starburst galaxies. These galaxies are also characterised by an extremely high rate of evolution with redshift up to $z \sim 1.5$ and significantly contribute to the cosmic far-IR extragalactic background.

1. New Facts from Deep Sky Explorations at Long Wavelengths

Observations at wavelengths longer than a few µm are essential to study diffuse media in galaxies, including all kinds of atomic, ionic and molecular gases and dust grains. By definition, they are particularly suited to investigate the early phases in galaxy evolution, when a very rich ISM is present in the forming systems.

Unfortunately, the IR and sub-millimetre constitute a very difficult domain to access: astronomical observations are only possible from space, apart from a few noisy atmospheric windows at $\lambda \sim 10$ and 850 µm where they can be done from dry sites on the ground.

1.1 Discovery of the Cosmic Infrared Background

During the last few years, a variety of observational campaigns in the far-IR/sub-mm have started to provide results of strong cosmological impact, by exploiting newly implemented ground-based and space instrumentation.

One important discovery in the field during the last few years concerned an intense diffuse isotropic flux detected at far-IR/sub-mm wavelengths in the all-sky maps imaged by the Cosmic Background Explorer (Puget et al. 1996; Hauser et al. 1998). The isotropy of this background (henceforth the Cosmic IR Background, CIRB) was immediately interpreted as due to an extragalactic source population, but its intensity turned out to be far in excess of the level expected from local galaxies, as observed by IRAS and by millimetre telescopes (e.g. Franceschini et al. 1998). What is remarkable in this context is that the bolometric CIRB flux is at least a factor of two larger than the integrated stellar light from galaxies at any redshifts, as sampled by the HST in ultra-deep imaging surveys.

Then the only viable interpretation for the CIRB was to correspond to an ancient phase in the evolution of galaxies characterised by an excess emission at long wavelengths, naturally interpretable as an effect of a rich and dusty interstellar medium. The large energetic content of the CIRB compared to the optical already sets interesting constraints on galaxy evolution in very general terms, as our team will report in due course.

1.2 Deep SCUBA surveys resolve part of the CIRB at the mm

Particularly relevant have been the deep explorations performed by the

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[1] ISOCAM was a mid-infrared camera, one of the four instruments on board the Infrared Space Observatory (ISO).