Gamma-Ray Bursts: the Most Powerful Cosmic Explosions

L. KAPER[1], A. CASTRO-TIRADO[2], A. FRUCHTER[3], J. GREINER[4], J. HJORTH[5], E. PIAN[6], M. ANDERSEN[7], K. BEUERMANN[8], M. BOER[9], I. BURUD[3], A. JAUNSEN[5], B. JENSEN[5], J.M. CASTRO CERÓN[10], S. ELLISON[11], F. FRONTERA[12], J. FYNBO[13], N. GEHRELS[14], J. GOROSABEL[2], J. HEISE[15], F. HESSMAN[16], K. HURLEY[17], S. KLOSE[16], C. KOUVELIOTOU[18], N. MASETTI[12], P. MØLLER[13], E. PALAZZI[12], H. PEDERSEN[5], L. PIRO[19], K. REINSCH[8], J. RHOADS[3], E. ROL[1], I. SALAMANCA[1], N. TANVIR[20], P.M. VREESWIJK[1], R.A.M.J. WIJERS[1], T. WIKLIND[21], A. ZEH[16], E.P.J. VAN DEN HEUVEL[1]

[1]Astronomical Institute "Anton Pannekoek", Amsterdam, The Netherlands; [2]IAA-CSIC, Granada, Spain; [3]STScI, Baltimore, USA; [4]MPE Garching, Germany; [5]Copenhagen University Observatory, Denmark; [6]Trieste, Italy; [7]Potsdam, Germany; [8]Universitäts Sternwarte, Göttingen, Germany; [9]CESR/CNRS, Toulouse, France; [10]Real Instituto y Observatorio de la Armada, Cádiz, Spain; [11]ESO Paranal, Chile; [12]Bologna, Italy; [13]ESO Garching, Germany; [14]NASA/GSFC, Greenbelt, USA; [15]SRON Utrecht, The Netherlands; [16]Thüringer Landessternwarte (Tautenburg, Germany); [17]UC Berkeley, Space Sciences Laboratory, USA; [18]NASA/MSFC, Huntsville, USA; [19]Rome, Italy; [20]Hertfordshire, United Kingdom; [21]Onsala, Sweden

1. Introduction

Gamma-ray bursts (GRBs) are brief flashes of cosmic γ-rays, first detected in data from the US military *Vela* satellites in 1967 that were launched to verify the Nuclear Test Ban Treaty (Klebesadel et al. 1973). Lacking a distance scale, the physical nature of GRBs remained a mystery for thirty years. Their cosmological origin was suggested by their isotropic sky distribution, demonstrated in the early 1990s by the BATSE experiment onboard the *Compton Gamma-Ray Observatory* (Fig. 1).

However, the definite proof of their distant, extragalactic nature came from the discovery of their rapidly fading *afterglows* at X-ray, optical, and radio wavelengths in 1997, thanks to the alerts of the Italian-Dutch *BeppoSAX* satellite. Absorption and emission lines in the afterglow spectra provided redshifts in the range z = 0.1–4.5, corresponding to distances of several billion light-years out to the edge of the visible universe. This made it clear that GRBs represent the most powerful explosions in the universe since the Big Bang.

There are strong indications that GRBs are caused by highly relativistic, collimated outflows powered by the collapse of a massive star or by the merger of two compact objects. Their enormous brightness make GRBs powerful probes of the distant and early universe, yielding information on the properties of their host galaxies and the cosmic star-formation history.

2. The GRACE consortium

Since the discovery of the first GRB afterglow on 28 February 1997 (Costa et al. 1997, Van Paradijs et al. 1997, Metzger et al. 1997), active collaborations between many observatories around the world has resulted in a timely and detailed study of several dozen GRBs. From the start ESO has played a very important role in the identification and analysis of the optical and infrared afterglows. Gamma-ray detectors onboard spacecraft orbiting the Earth or exploring the solar system provide the GRB alerts, which are promptly announced on the *Gamma-ray burst Circular Network* (GCN); these trigger immediate follow-up observations at ground-based observatories. By building up a network of astronomers at observatories all around the world, it becomes possible to quickly (within hours) respond to a GRB alert (from one or both hemispheres) and to locate and monitor the afterglow.

Here we report on behalf of the GRACE consortium, the *Gamma-Ray burst Afterglow Collaboration at ESO*[1]. The GRACE consortium was awarded an ESO Large Programme that started in April 2000 and ended in March 2002. So far, the GRACE collaboration has identified most of the known GRB optical counterparts and has measured about two thirds of all known GRB redshifts. Currently, ESO observing time is allocated to GRACE through normal Target of Opportunity one-semester programmes. Our collaboration is also involved in GRB follow-up programmes awarded observing time on the *Hubble Space Telescope* (HST), the *Chandra* X-ray observatory, and INTEGRAL.

GRACE consists of teams of astronomers ("nodes") based in Denmark, Germany, Italy, Spain, the Netherlands, the United Kingdom and the United States of America. The nodes take turns for being "on duty" for periods of two weeks. Starting September 2002 our collaboration will be supported by a Research and Training Network funded by the European Commission for a period of four years.

3. GRBs and their afterglows

GRBs are short flashes of γ-rays, with a duration ranging from several milliseconds to tens of minutes, and in most cases an observed peak energy around 100 keV. The daily rate of GRBs, detectable from Earth, is about two (Paciesas et al. 1999). The γ-ray light curves are extremely diverse, some very smooth, others with numerous spikes. BATSE data showed that there are two distinct classes of GRBs: a class with a short duration (less than 2 seconds) and relatively hard spectra, and a class of long-duration bursts with softer spectra. It is important to note that only afterglows of the latter population have been observed so far: it is not known whether short bursts produce afterglows at all. The best limit obtained so far is for the short/hard HETE-II burst GRB 020531, for which Salamanca et al. (2002) did not detect any afterglow candidate brighter than V ~ 25, just 20 hours after the alert.

In a previous *Messenger* paper (Pedersen et al. 2000) the first scientific break-throughs in this field were reported. The Italian-Dutch *BeppoSAX* satellite played a crucial role in these discoveries by rapidly determining the position of a GRB with arcminute precision. Arcminute-sized error boxes match the typical field size of modern (optical) detectors, so that it became feasible to detect the GRB afterglows,

[1]http://zon.wins.uva.nl/grb/grace/

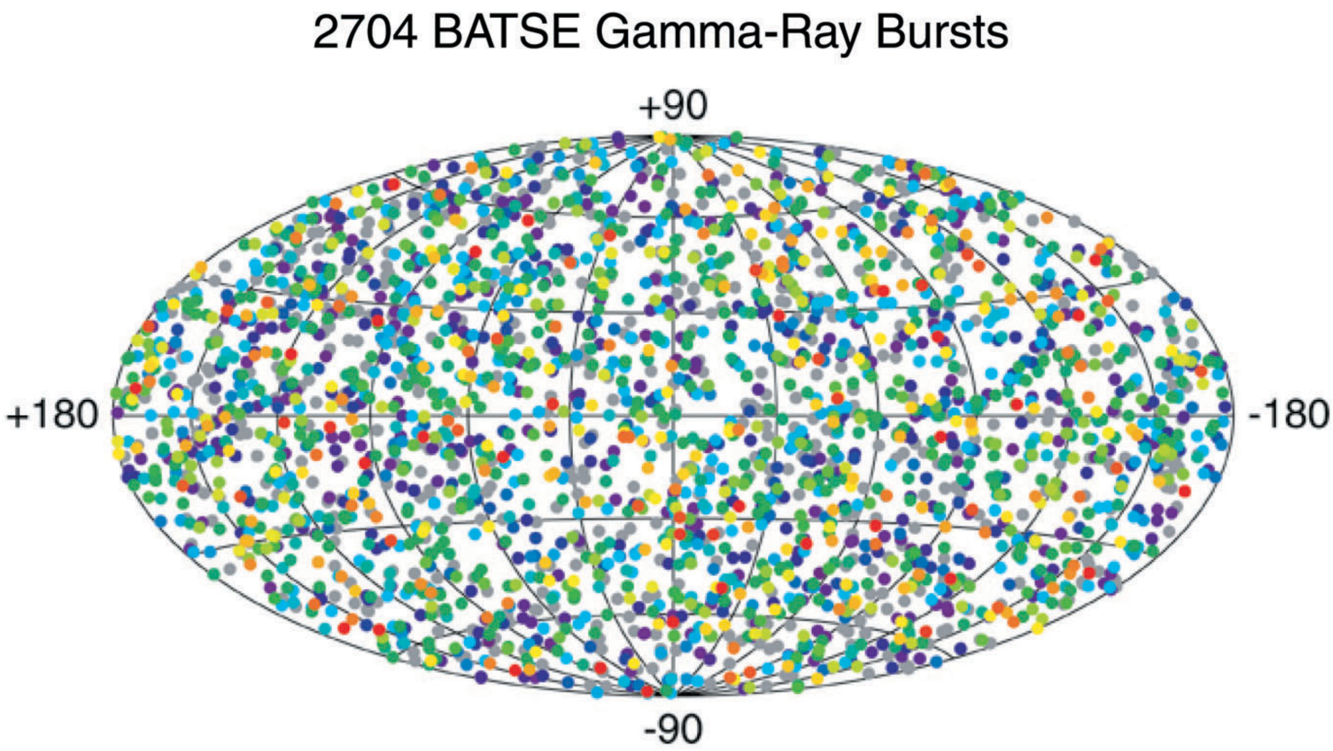

Figure 1: This map shows the locations of a total of 2704 GRBs recorded with BATSE on board NASA's Compton Gamma-Ray Observatory *during its nine-year mission. The projection is in galactic coordinates; the plane of the Milky Way Galaxy is along the horizontal line at the middle of the figure. The burst locations are colour-coded based on the fluence, which is the energy flux of the burst integrated over the total duration of the event. Long-duration, bright bursts appear in red, and short-duration, weak bursts appear in purple (credit BATSE team).*

which fade quickly, on a timescale of only a few days (the typical time profiles are $t^{-\alpha}$, with $\alpha \sim 1–2$).

The *High Energy Transient Explorer II* (HETE-II), launched in October 2000, was designed to provide very rapid (< 1 minute) and very precise positions (error boxes down to arcseconds) of both long- and short-duration bursts. This mission has been one of the main drivers of our ESO Large Programme, but so far only few accurate HETE-II positions have become available. Besides HETE-II, satellites in the *Interplanetary Network* (IPN) provide burst positions, though at a low rate. The *BeppoSAX* mission was terminated on April 30, 2002, exactly 6 years after its launch.

With *Integral* (launch October 2002) and *Swift* (2003) the rate of GRB alerts will definitely increase again. In preparation for these missions, robotic telescopes are installed at ESO La Silla to perform prompt follow-up of GRB alerts. Given the expected high data rate, a fast afterglow identification pipeline is necessary. Our consortium has developed such a pipeline using colour-colour discrimination techniques. The efficiency of this procedure was demonstrated by the discovery, at ESO, of the optical and near-infrared counterpart of GRB 001011 (Gorosabel et al. 2002a).

Since the advent of rapid (within a few hours to days) GRB locations[2], 39 alerts resulted in the detection of an

[2]http://www.aip.de/People/Greiner/grbgen.html

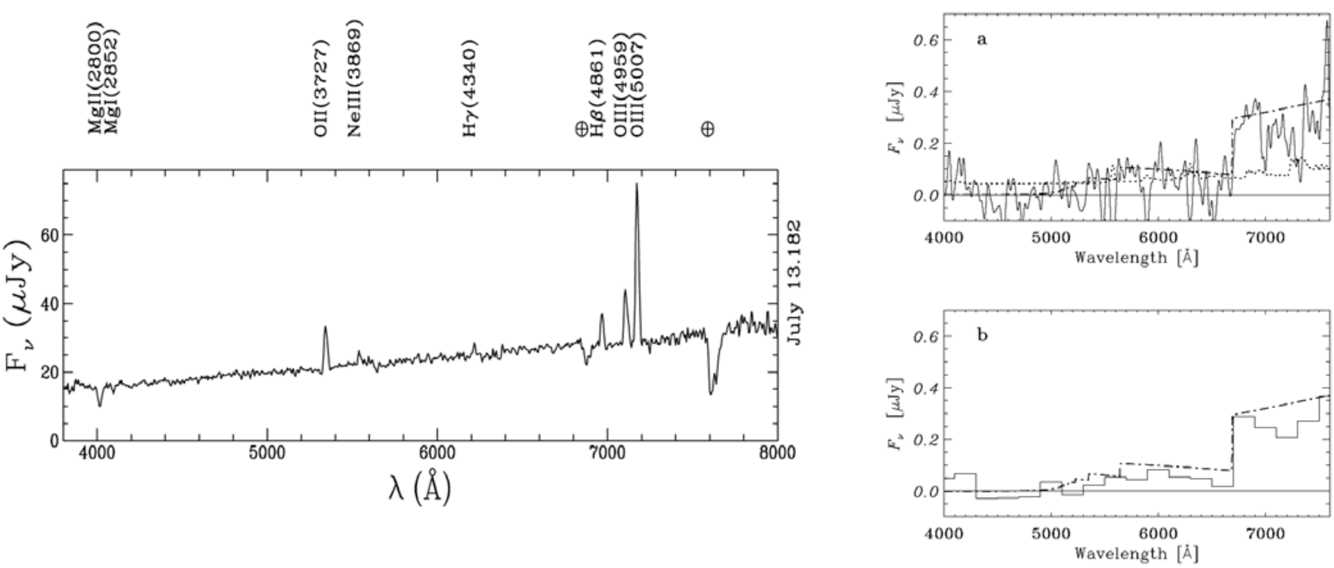

Figure 2: Left: VLT spectrum of GRB 990712 taken 12 hours after the burst. Absorption lines of Mg I and Mg II are detected, as well as several emission lines from the underlying bright (V ~ 22) host galaxy (from Vreeswijk et al. 2001). The redshift of the galaxy is z = 0.43. Right: A low-resolution FORS spectrum of the currently most-distant GRB 000131 at z = 4.5 (from Andersen et al. 2000). The redshift is determined from the Lyman break.

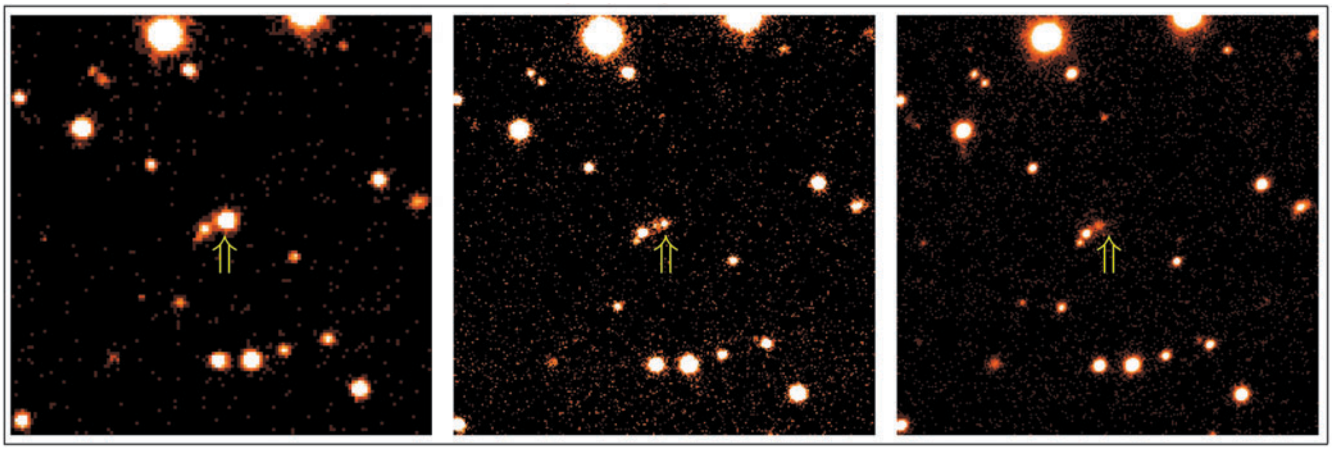

Figure 3: The fading afterglow of GRB 011121 at near-infrared wavelengths (1.2 μm, J band, Greiner et al. 2002). The field size is 40 × 40 arcseconds, North is up and East is to the left. On November 22, 2001, the afterglow is detected by NTT/SOFI at J = 17.5; 2 days later the afterglow has faded to J = 20.9. On February 9, 2002, the afterglow is not detected anymore (J > 24) in this superb VLT/ISAAC image (seeing 0.4 arcsecond). The light sources near the position of GRB 011121 might represent some bright regions in the host galaxy.

X-ray afterglow; 32 optical afterglows have been found (of which more than half were discovered by our collaboration), and 20 radio afterglows (status July 1, 2002). For many GRBs no afterglow is found. Adverse observing conditions can explain many of these non-detections. For example, the optical afterglow of GRB 000630 had faded to an R-band magnitude of 23 just 21 hours after the burst (Fynbo et al. 2001), and would certainly have remained undetected in searches initiated a bit later. In some cases, however, another explanation is needed. For example, the extinction by gas and dust in the circumburst environment might hinder the detection of an afterglow at rest-frame UV and optical wavelengths, or it may be too faint or even absent. The nature of these *dark* bursts remains to be resolved.

For 24 GRBs the distance has been determined. The GRB spectrum itself is featureless (consistent with optically thin synchrotron emission), but absorption and/or emission lines formed in the GRB host galaxy, or the position of the Lyman break (912 Å), provide the redshift (Fig. 2). The majority of redshifts are in the range between 0.5 and 1.5. The current record holder, achieved with the VLT, is GRB 000131 with z = 4.5, corresponding to a "distance" (look-back time) of 13 billion light-years (Andersen et al. 2000, ESO press release 20/00).

That GRBs can potentially probe the very distant universe was demonstrated by the impressive burst detected in January 1999: GRB 990123 (Akerlof et al. 1999). Within the first minutes following the burst, its optical afterglow reached visual magnitude V = 9, i.e. observable with a pair of binoculars. It was briefly one million times brighter than a supernova. This particular burst, at z = 1.6, would have been detectable (at its maximum, in the K band) with the *Very Large Telescope* up to a redshift of about 15. With *Swift,* which will provide accurate burst positions within a few minutes, many such bright early afterglows become detectable.

4. Evidence for collimation

Assuming isotropic emission, the measured distances imply peak luminosities of 10^{52} erg/s (10^{45} Watt). Thus the peak luminosity of each event corresponds to about 1% of the luminosity of the visible universe! The resulting energy budget is about 10^{53} erg, which is actually comparable to the total amount of energy released during a stellar collapse (supernova). The measured rate of GRBs corresponds to about one per million year per galaxy.

There is mounting evidence, however, that γ-ray bursts are collimated into jets, with opening angles of a few degrees only. This evidence comes from the interpretation of the occurrence of a kink in the slope of the afterglow light curves, and from the detection (in a few cases) of polarization (see ESO press release 08/99). Also, the total isotropic energy inferred for GRB 990123 is uncomfortably high (to be explained by a stellar-collapse model), but would be reduced by a factor of 500 if the energy were emitted into a cone with an opening angle of 5 degrees.

Frail et al. (2001) determine the jet opening angle of several GRB afterglows and show that the spread in the output energy distribution of their sample becomes much narrower when taking the collimation into account, with a mean energy output of 2×10^{51} erg. They suggest that this may be the standard energy reservoir for all GRBs. Though speculative, the implications of this finding are great if these intrinsically bright GRBs can be used as standard candles at high redshifts, e.g. to measure the expansion rate of the Universe. Another consequence of the collimation is that the GRB rate also increases by a factor of 500, and that the vast majority of bursts are not visible.

5. The origin of GRBs: possible progenitors

From a variety of arguments, such as their total energy and the evidence for collimation, the general expectation is that a system consisting of a black hole and a surrounding accretion torus is powering the GRB. Such a setting, just before the GRB goes off, can occur in several ways. One way is the merging of a binary neutron-star system, like the Hulse-Taylor binary pulsar, or a neutron star and a black hole (e.g. Lattimer & Schramm 1974, Eichler et al. 1989). Another popular model involves the core collapse of a rapidly rotating massive star, the "collapsar" model (Woosley 1993, Paczynski 1998, MacFadyen & Woosley 1999).

There are several indications that the observed population of GRB afterglows, i.e. the long-duration bursts, is best explained by the latter model. The first indication comes from the models themselves. The collapsar model naturally produces bursts that have a duration longer than a few seconds, but cannot make short bursts. On the other hand, the merger model can produce short bursts, but has problems keeping the engine on for longer than a couple of seconds. The clear distinction between short- and long-duration bursts suggests that both progenitor models may be at work in nature.

6. The supernova connection

Another indication that long-duration GRBs are related to the core collapse of a massive star is that some GRBs seem to be associated with a supernova (SN). The first evidence for a supernova connection came from GRB 980425/SN1998bw (Galama et al. 1998; ESO Press Release 15/98). This supernova, approximately coincident in time and position with GRB 980425, was of the rare type Ic, and at radio wavelengths the brightest supernova ever detected. Interpretation of the light curve indicated that during this supernova a black hole was formed (Iwamoto et al. 1998). However, the amount of prompt γ-ray emission was very modest, which makes GRB 980425, the closest GRB at a redshift of $z = 0.0085$, a peculiar event.

In the mean time, evidence has been found that several GRB afterglow light curves show a so-called supernova bump, i.e. a bump in the light curve at a time interval compatible with the rise time of a SN, assuming it has gone off simultaneously with the GRB. The bump would thus represent the SN maximum light. Amongst them is the recent burst GRB 011121 (Fig. 3), which was followed up by our collaboration with ESO telescopes in several wavelength bands (Fig. 4, Greiner et al. 2002). Emission lines produced by the host galaxy indicate a redshift of 0.36. The late-time light curve shows a bump, some 10 days after the burst when the GRB afterglow has faded by a factor of 250. After correcting for the flux contribution and extinction due to the host galaxy, the late-epoch light curve is consistent with a SN similar to SN1998bw (taking into account the difference in redshift).

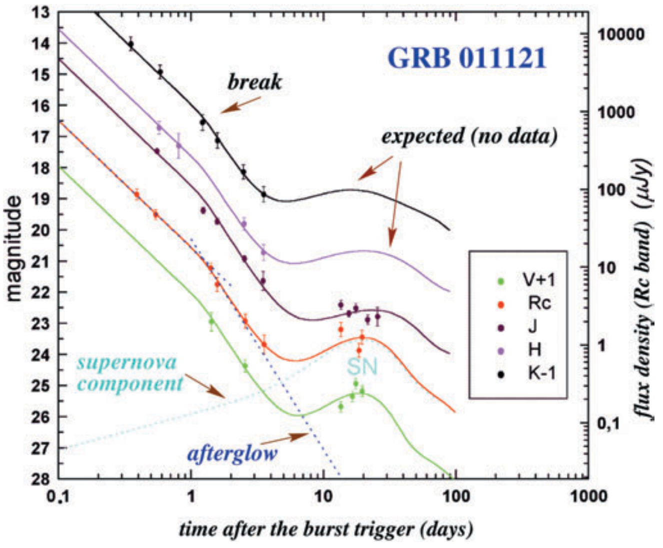

Figure 4: The light curve of GRB 011121 at optical and near-infrared wavelengths. The blue dotted line represents the contribution to the light of the GRB afterglow. About 10 days after the burst the light curve shows a bump, indicative of an accompanying supernova,shown in magenta (Greiner et al. 2002).

7. GRB host galaxies

For practically all GRB afterglows with an accurate location, a host galaxy has been detected. In nearly all cases the burst is located within the optical (rest frame UV) extent of the galaxy. This, in combination with the blue colours of the galaxies, suggests that GRBs originate in galaxies with a relatively high star-formation rate. The collapsar model predicts that GRBs will occur in regions where active star formation is taking place (see, e.g., the VLT observations of the host of GRB 001007, Castro Cerón et al. 2002). Neutron-star binaries do not necessarily reside in star-forming regions. Due to the kick velocities received during the two supernova explosions forming the neutron stars, such binaries are high-velocity objects. As the merging process of the binary, driven by the emission of gravitational radiation, can take up to a billion years, the binary may have travelled several thousand light-years before producing a GRB.

With the *Hubble Space Telescope* (HST) the morphology of the GRB host galaxies is studied in detail. Figure 5 shows an HST/STIS image of the galaxy hosting GRB 990705 (Andersen et al. 2002). It is a giant grand-design spiral at a distance of about 8 billion light-years with a diameter in excess of 150,000 light-years. Apparently, the GRB went off in the outskirts of one of the spiral arms.

For several host galaxies the star-formation rate has been determined. The emission lines in the VLT spectrum of the host galaxy of GRB 990712 (Fig. 2) are produced by H II regions in that galaxy. The strengths of these lines indicate an (extinction-corrected) star-formation rate of about 35 $M_\odot$ yr^{-1} (Vreeswijk et al. 2001). For some host galaxies even higher rates of star formation are claimed, up to 1000 $M_\odot$ yr^{-1} (e.g. Berger et al. 2001). These observations show that at least some of the GRB host galaxies belong to the class of *starburst* galaxies.

Thus, the observations of GRB host galaxies support the collapsar model. Since these galaxies, due to their distance, are often very faint, the bright GRB afterglow provides a unique opportunity to study the gas and dust content of the host galaxy. The metallicity and star-formation rate of these relatively young galaxies can be measured. As part of our host-galaxy programme, the spectral energy distribution (SED) of the host galaxy of GRB 000210 has been determined. Fitting the observed SED with a grid of synthetic templates, the age (0.2 Gyr) of the dominant stellar population and the galaxy's photometric redshift ($z = 0.84$) is determined (Gorosabel et al. 2002b). If the collapsar model is right, the GRB rate is a direct measure of the formation rate of massive stars in the early universe, an important quantity for the study of the star-formation rate as a function of redshift.

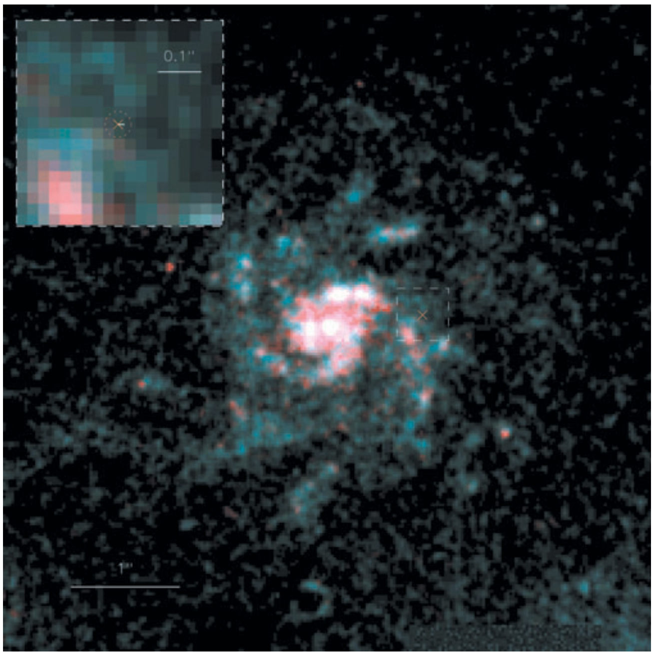

Figure 5: HST/STIS image of the host galaxy of GRB 990705. It is a grand-design spiral at a distance of 7.6 billion light-years. North is up and East is to the right. The location of the GRB is marked with a cross; the red circle gives the 3σ error on its position. Note that, due to the redshift, the image shows the rest-frame UV light emitted by the galaxy (Andersen et al. 2002).

8. Remaining fundamental questions

Much progress has been made in understanding the GRB phenomenon. However, many fundamental questions remain to be addressed. What is the origin and nature of the short-duration bursts? Do they produce afterglows, like the long bursts? Are all GRBs associated with a supernova, and if so, why do we rarely observe it? Is this related to the difference in collimation of the γ-rays with respect to the optical light? Are GRBs preferentially found in galaxies undergoing a starburst?

The number of GRBs with optical counterparts roughly corresponds to the number of supernovae observed before 1934, when Baade and Zwicky suggested that supernovae might be powered by the gravitational collapse to a neutron star. The collapsar model, a massive star collapsing to a black hole, has now become widely accepted to explain GRBs. But, just as Baade and Zwicky failed to anticipate Type Ia supernovae, the collapsar model, even if correct, may be incomplete. A challenging future lies ahead.

We would like to acknowledge the support which our collaboration has received from the staff at several observatories.

References

Akerlof, C., Balsano, R., Berthelemy, S., et al. 1999, *Nature* **398**, 400.
Andersen, M.I., Hjorth, J., Pedersen, H., et al. 2000, *A&A* **364**, L54.
Andersen, M.I., Hjorth, J., Gorosabel, J., et al. 2002, *A&A*, submitted.
Berger, E., Kulkarni, S.R., Frail, D.A. 2001, *ApJ* **560**, 652.
Castro Cerón, J.M., Castro-Tirado, A.J., Gorosabel, J., et al. 2002, *A&A*, in press.
Costa, E., Frontera, F., Heise, J., et al. 1997, *Nature* **387**, 783.
Eichler, D., Livio, M., Piran, T., et al. 1989, *Nature* **340**, 126.
Fynbo, J.U., Jensen, B.L., Gorosabel, J., et al. 2001, *A&A* **369**, 373.
Frail, D.A., Kulkarni, S.R., Sari, R., et al. 2001, *ApJ* **562**, L55.
Galama, T.J., Vreeswijk, P.M., Van Paradijs, J., et al. 1998, *Nature* **395**, 670.
Gorosabel, J., et al. 2002a, *A&A* **384**, 11.
Gorosabel, J., et al. 2002b, in preparation.
Greiner, J., Klose, S., Zeh, A., et al. 2001, *GCN* **1166**.
Iwamoto, K., Mazzali, P.A., Nomoto, K., et al. 1998, *Nature* **395**, 672.
Lattimer, J.M., Schramm, D.N. 1974, *ApJ* **192**, L145.
Klebesadel, R.W., Strong, I.B., Olson, R.A. 1973, *ApJ* **182**, L85.
Kouveliotou, C., Meegan, C.A., Fishman, G.J., et al. 1993, *ApJ* **413**, L101.
MacFadyen, A.I., Woosley, S.E. 1999, *ApJ* **524**, 262.
Meegan, C.A., Fishman, G.J., Wilson, R.B., et al. 1992, *Nature* **355**, 143.
Metzger, M.R., Djorgovski, S.G., Kulkarni, S.R., et al. 1997, *Nature* **387**, 878.
Paciesas, W.S., Meegan, C.A., Pendleton, G.N., et al. 1999, *ApJS* **122**, 465.
Paczynski, B. 1998, *ApJ* **454**, L45.
Pedersen, H., et al. 2000, *The Messenger* **100**, p. 32.
Salamanca, I., et al. 2002, *GCN* **1443**.
Van Paradijs, J.A., Groot, P.J., Galama, T., et al. 1997, *Nature* **386**, 686.
Vreeswijk, P.M., Fruchter, A.S., Kaper, L., et al. 2001, *ApJ* **546**, 672.
Woosley, S.E. 1993, *ApJ* **405**, 273.

Cataclysmic Variables: Gladiators in the Arena

R.E. MENNICKENT[1], *C. TAPPERT*[1], *M. DIAZ*[2]

[1]*Departamento de Física, Universidad de Concepción, Chile*
[2]*Instituto Astronomico e Geofisico, Universidade de São Paulo, Brazil*

1. Warriors and weapons

Life can be different for individuals growing up alone or closely interacting with members of their community. The same is true for stars, which present interesting phenomena when they are forced to evolve together in close interaction. This is the case for cataclysmic variables (CVs, Fig. 1), consisting of a red dwarf filling its Roche lobe and transferring matter onto a white-dwarf (WD) companion. If the white dwarf is a non-magnetic one, the orbiting gas interacts with itself dissipating energy by viscous forces, forming a luminous accretion disc around the white dwarf. The WD reacts by emitting X-rays and UV radiation from the region where the inner disc reaches its surface. As a result, part of the red dwarf atmosphere is irradiated and mildly heated, and possibly the upper accretion disc layers evaporated. It has been suggested that after a long-time of having accreted matter, the outer layers of the white dwarf eventually undergo a thermonuclear runaway in a so-called nova explosion.

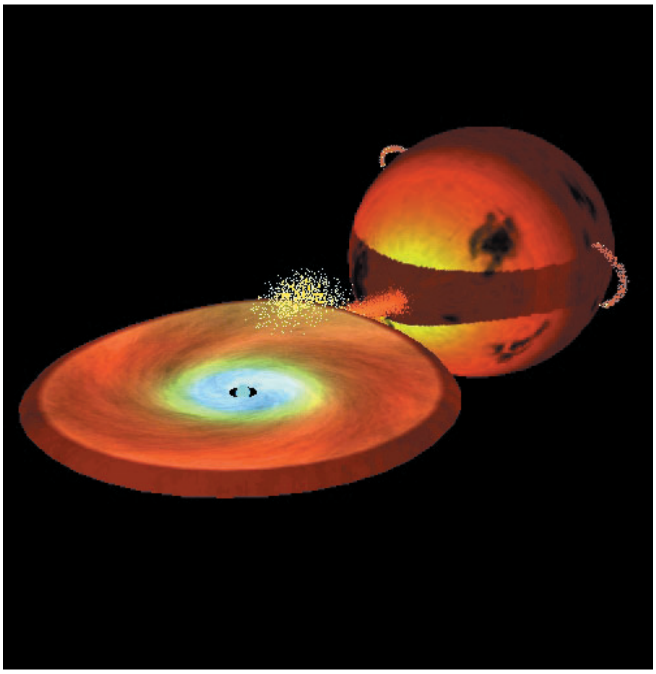

Figure 1: Computer-generated view of a cataclysmic variable star by Andrew Beardmore. The donor, usually a M-type star, transfers matter onto a white dwarf. Due to viscous forces, an accretion disc is formed. Colours represent different temperatures, from the higher (white) to the lower ones (red-black). Irradiation of the donor by the white dwarf and disc shading are also shown, as well as the hotspot in the region where the gas stream impacts the disc.

Here we present some results of our recent research in the area of dwarf novae, a subclass of cataclysmic variables showing semi-regular outbursts in time scales of days to years with typical amplitudes of 2–6 mags. The origin of these dwarf-nova outbursts is not a thermonuclear runaway as in the case of a nova outburst, but a sudden jump in disc viscosity and mass transfer rate as a result of the hydrogen ionization. In this article we do not go into deep details. Instead, we will illustrate the application of some standard techniques in the field of CVs aimed to explore disc dynamics and also to reveal the nature of the donor star. The latter point is especially important to constrain theories of CV evolution.

A typical spectrum of a dwarf nova in quiescence is shown in Figure 2. It is