X-Shooter and the GRBs

Hector Flores
GEPI, Observatoire de Paris Meudon
GRBs - Discovery (1967-1973)

- US Vela Nuclear test detection satellites
GRB, who you are...

- **GRBs remained a complete mystery for almost 30 years!**
- More than 100 different theories:
  - Magnetic flares
  - Black Hole evaporation
  - Anti-matter accretion
  - Deflected AGN jet
  - Magnetars, Soft Gamma-Ray Repeaters (SGRs)
  - Mini BH devouring NS
  - ....
- **message from the Aliens**
<table>
<thead>
<tr>
<th>Model</th>
<th>Author</th>
<th>Year</th>
<th>Reference</th>
<th>Main Body</th>
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Note: most are Galactic
Compton Gamma-Ray Observatory (CGRO)

Launched in 1991 (orbit above atmospheric absorption)

• BATSE (20 keV-1 MeV):
  • extremely sensitive gamma-ray detector (scintillator)
• EGRET (20 MeV-30 GeV):
  • Pair production detector

Looked at the whole sky

• GRB detection rate ~ 1 GRB/day
• thousands of GRBs detected over the whole mission
First lesson: Isotropic on the sky
Isotropy = Cosmological distance

- Objects that follow the Galactic distribution (of mass, stars etc) look different
- GRBs are NOT Galactic
- They are cosmological
Cosmological?

• BeppoSax satellite made the breakthrough in 1997

• Detected in low-energy γ rays

• Localized in X rays at the same time

• People found optical counterpart ~1 day later (arcsec resolution)
Cosmological!

- A month later the region is observed with a large telescope
  - From lines in the spectrum of the galaxy the redshift is measured

- Today we have more than ~200 redshift measurements

- The furthest away at $z \sim 8.2!$ (600 Myr after the big Bang)
The last 12 years, it is verified that γ-ray bursts are cosmological

- Detecting emission that follows the burst in the X-rays, optical, radio
- Good localization (less than arcmin)
- Detecting the galaxies they come from
- Measuring the redshift of the galaxies
Second lesson

- 2 populations of GRBs:
  - Short-Hard / Long-Soft Bursts
  - Long Duration $T > 2$ sec

![Burst duration](image1)

![Hardness-duration diagram](image2)
GRB lightcurve / spectrum

- Non thermal prompt emission
- Best spectral fit: smoothly joining broken power law

- **Compactness problem:**
  - Emitting region optically thin if emitting material has Lorentz factor > 100
  - Ultrarelativistic outflow (fastest bulk flow in the universe)

Briggs et al. 1999
A burst: the sum of two phenomena

- the classical GRB phenomenon, the “prompt emission”
- the subsequent fading emission, the “afterglow emission”

When in 1997 BeppoSAX discovered a fading emission following the GRB (Costa et al. 1997)

- Observed at all wavelengths (radio to X-ray)
- Detectable for days to weeks.
GRB progenitors

ms time variability implies a compact object

Energy $> \sim 10^{52}$ erg:
Stellar mass black hole

Forming a black hole
- Merging of two compact objects: SHORT GRB (<2s)
- Gravitational collapse of a massive star ($M > 20 M_\odot$): LONG GRB (>2s)

Woosley & McFadyen 1999; Heger et al. 2001
For the short ones...

- Neutron stars merging model

- Short duration GRBs (<2sec):
  - Appear dimmer by a factor 10
  - Not observed on star formation regions
  - Have a large fraction of hard gamma-rays
  - Too fast to be explained with the ‘collapsar’ model

- Possible model → Merger of two neutron stars:
  - The stars lose angular momentum radiating gravitational waves
  - Eventually they collide forming a Black Hole

(Models with Neutron star - BH systems have been also proposed)

Some groups propose that shorts GRBs are Good candidate for gravitational wave detection

Other progenitor still possible (giant magnetar flares...)

Gravitational waves

Can be produced

- Before the collapse of the binary progenitor (efficient)
- During the bounding of the core-collapse (inefficient)

Main target are short bursts

To date, no detection

Due to small volume sampled (detection limit is \( \sim 100 \) Mpc)

Next step: new instruments

- Should trigger on GRBs

\( \rightarrow \) Will provide information on the progenitor mass, geometry.
High energy photons

- GRB 940217 (Hurley et al. 1994): detected by EGRET, with a 18 GeV photon;
- GRB 941017 (Gonzalez et al. 2003)
- GRB 090514B (AGILE collaboration): detected in the GRID

However, no clear idea of what happen after a few MeV.
- Unknown GRB sky above 100 GeV.

Cosmic rays

During the acceleration of the fireball, baryons, electrons and positrons are accelerated up to relativistic velocities
- Possible candidate to produce energetic CRs
- But not clear if GRB produce detected CRs

To date, no claimed detection from any GRB
(but we detect only ~ 40% of GRBs seen on-axis, and none can be seen off-axis !)
For the long-soft burst:
Evidence for the core collapse model

• **Long-Soft Bursts** located in **star forming region** (irregular galaxies, arms of spiral galaxies) were massive stars are always found

• **Supernovae connection:**
  • Bump observed in the optical afterglow
  • Connection with Type Ib/c (core-collapse supernovae)
GRB-SN connection


- Exploded within 1 day from the GRB. Chance P=10^{-4}

Type Ic supernova, d = 40 Mpc
Modeled as the 3 x 10^{52} erg explosion of a massive CO star
(Iwamoto et al 1998; Woosley, Eastman, & Schmidt 1999)

GRB 8 x 10^{47} erg; 23 s
“Bumps” seen in the optical afterglows of at least three GRBs - 970228, 980326, and 011121 – at the time and with a brightness like that of a Type I supernova
The GRB-Supernova Connection

**GRB 060218** (the second closest GRB)

$$z = 0.03352$$

Detailed spectroscopic monitoring

Broad-lined “**hypernova**”
GRB and cosmology

GRBs can be used to study cosmology

- Distant events
- Present empirical relations
- Good complement to SNe

But...

No nearby event to calibrate any standard candle

Actual solutions

- Do not care (may be problematic)
- Use sample of same distant events (statistical significance still low)
- Try to understand the empirical standard candles (complicated, but accurate)

They claims that GRBs can be used as cosmological RULERS

Ghirlanda et al. 2004

Supernovae

GRBs

redshift

Luminosity distance

GRB 000519

SN Ia

Δ(m-M)[mag]
Afterglows before SWIFT

Afterglows => redshift => distance & energetics

Cosmological events: \( <z> = 1 \)

GRBs energies: \( 10^{51} \text{ – } 10^{54} \text{ erg} \) => \( 10^{51} \text{ erg} \) if collimated

Very rare in the Universe (~1/100 of SNe)

**LONG GRBs**

* Association with core-collapse SNe
* Star-forming host galaxies
* Connection with cosmic star formation

**SHORT GRBs**

* Binary compact object binary mergers
SWIFT: Optical-NIR observations

- 40-50% of the Swift GRBs have no optical counterpart or in any case the optical counterpart is very weak (absorption? intrinsically optically weak? high redshift?)

- The average redshift is quite high \(<z>\sim 2.5\) to be compared with a value of \(<z>\sim 1\) expected before the launch of Swift. Due to the higher sensitivity and harder energy band of BAT with respect to BeppoSAX WFC and HETE II and also to faster reaction in the optical-NIR follow-up (e.g. Fiore et al. 2007, AA 470. 515)

GRBs are thus ideal probes of the high-redshift Universe
Looking at the origins of the universe

Example at $z = 6.3$

Ly$\alpha$ dropout suppressing optical emission

Tagliaferri et al. 2005

Spectroscopic confirmation!
Kawai et al. 2006
The Early Universe Composition

Dust composition/evolution: the case of GRB 050904 @z=6.3
A large X-ray absorption and UV dust extinction is observed.

**Haislip WFCAM-UKIRT**
~0.5 days
Lyα corr. = 3.02

**Tagliaferri FORS-VLT**
~1 day
Lyα corr. = 1.27

**Haislip GMOS-Gemini**
~3 days
Lyα corr. = 2.38

**QSO@6.2 extinction curve**
0.5 day $A_{3000}=0.89 \pm 0.16$
1 day $A_{3000}=1.33 \pm 0.29$
3 days $A_{3000}=0.46 \pm 0.28$

$NH \sim 10^{23} \text{ cm}^{-2} \Rightarrow AV/NH \sim 50 \text{ times lower than Galactic!!}$

@z~6 no dust from AGB stars.

Much less dust and much smaller $A_V/N_H$

Less dust => less extinction @z>5 => high-z afterglows easier to detect => Swift GRB sample with redshifts not strongly biased against high-z objects.
• There may be several hundred unusual explosions for every gamma-ray burst we see.

  Very approximately 1% of all supernovae make GRBs but we only see about 0.5% of all the bursts that are made – a rare phenomenon.

• If typical GRBs are produced by massive stars, the star must have lost its hydrogen envelope before it died.

  A jet that loses its power source after the mean duration of 10 s can only traverse $3 \times 10^{11}$ cm. This is long enough to escape a Wolf-Rayet star but not a giant.

  ⇒ Not SN II!
And the HOST? Chasing hosts galaxies

Optically dark GRB

UVOT-enhanced X-ray position

(host galaxy)

X-ray position usually good enough

(Butler, Evans)
Host galaxies properties

Facts:

- Metal poor
- Irregulars
- Young stellar population

Han et al. 2009
Host galaxies properties

Facts:

Metal poor Irregulars Young stellar population
Host galaxies properties

Facts:

Metal poor Irregulars

Young stellar population

And now we known that are WR galaxies
Detection of WR in host galaxies

**Observations** FORS2 at $R \sim 1200$ of 8 GRBs (Hammer et al 2006)

Large variety of bumps (Guseva et al 2000)
Combining multi instrumental information

GRB980525 at z=0.0086
Detection of WR stars in host galaxies

1> WR star in SN region
SN1998, < 10 0 stars,
But [S/N]=0.24 (expected for rotating stars Hirschi et al, 2005)

+ of 2300 0 stars
&
80 to 100 WR stars
**GRB progenitors:** Always a gap between the position of GRB and a bright region (HII)

- GRB020903 $z=0.25$
  - HST/ACS Dec 2002
  - Compact region
  - Distance $800 \text{ pc}$
- GRB030329 $z=0.17$
  - HST/ACS Nov 2003
  - Compact region
  - Distance $600 \text{ pc}$
- GRB980425 $z=0.0086$
  - HST/ACS May 2005
  - Compact region
  - Distance $100 \text{ pc}$

Distance from 400 to 800 pc → a star will need 3 to 4 Myr at 200 to 300 km/s

**What mean?**
GRB/SN Ib-c: A runaway scenario

Star ejected ~ 3-4 Myr
Fast rotation: lost the H/He envelope

runaway, fast rotating massive stars expelled from superstellar clusters?
Even if properties of GRBs and GRBs host galaxies starting to be well known

Community requested an instrument to increase the positive identification of GRBs

- Identification of dark GRBs
- Construction of an homogeneous sample
Large wavelength range (IFU mode) open new possibilities

The main scientific aim will be the GRBs with the possibility of detecting the farthest sources at the reionization epoch or beyond (+ SNIa at z > 1 and X-ray Binaries)

Scientific return: more than 200n Guaranteed time ongoing:
GRBs: ToO for three years

GRBs host galaxies; two programs: One from Denmark (long slit) and another from an Italy-French collaboration (long slit and IFU)
X-shooter technical drivers

- High efficiency
  - Most efficient optical/nIR spectrograph in the world
- Large wavelength coverage
  - Atmospheric cut-off to near-IR (300 – 2500 nm)
  - Complete wavelength range in one shot (split in three arms using dichroics)
- Resolving power R ~ 7 000 - 12 000 with 0.6” slit:
  - 80-90% of all spectral elements are unaffected by sky lines ➔ sky-background limited
- Single instrument mode
  - Direct slit
  - IFU (image slicer)
- Only second-generation VLT instrument in Cassegrain
  - High efficiency, but flexure and weight limitations
X-shooter consortium

• ESO: PI S. D’Odorico, PM/SE H. Dekker
  Instrument scientist: J. Vernet
  - Detector systems
  - System integration

• Denmark: PI/PM P. Kjaergaard Rasmussen
  - Backbone
  - UV/VIS spectrographs

• Italy: PI R. Pallavicini, PM F. Zerbi
  - UV/VIS spectrographs
  - Instrument control software

• Netherlands: PI L. Kaper, PM R. Navarro
  - NIR spectrograph
  - Data reduction software

• France: PI F. Hammer, PM I. Guinouard
  - IFU
  - Data reduction software
## Observing modes and available slits

<table>
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<tr>
<th>Feature</th>
<th>Details</th>
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<td><strong>Wavelength range</strong></td>
<td>300-2500 nm split in 3 arms</td>
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<tr>
<td><strong>UV-Blue arm</strong></td>
<td>Range: 300-550 nm in 11 orders Resolution: 4500 (1&quot; slit) Detector: 4k x 2k E2V CCD</td>
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<tr>
<td><strong>Visual-red arm</strong></td>
<td>Range: 550-1000 nm in 14 orders Resolution: 7000 (1&quot; slit) Detector: 4k x 2k MIT/LL CCD</td>
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<tr>
<td><strong>Near-IR arm</strong></td>
<td>Range: 1000-2500 nm in 16 orders Resolution: 4500 (1&quot; slit) Detector: 2k x 1k Hawaii 2RG</td>
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<tr>
<td><strong>Slit width and length</strong></td>
<td>0.6 1.0 &amp; 1.5 -- 12&quot;</td>
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<td><strong>Beam separation</strong></td>
<td>Two high efficiency dichroics</td>
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<td><strong>Atmospheric dispersion compensation</strong></td>
<td>In the UV-Blue and Visual-red arms</td>
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<tr>
<td><strong>Integral field unit</strong></td>
<td>1.8&quot; x 4&quot; reformatted into 0.6&quot; x 12&quot;</td>
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X-Shooter can observe the GRBs till z=15

Wavelength position of absorption lines and Lyman-α forest as a function of redshift. To the right X-shooter spectral range with respect to UVES
X-shooter VIS first light images 19.07.2007
Performance

S/N = 10 in 1 hour per resolution element, no binning

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<td>K</td>
<td>18.7</td>
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- Atmosphere
- Telescope (M1 & M2)
- Dichroics
- Pre-slit optics and spectrograph optics
- Gratings
- Detectors

Total throughput > 25%
Best optical and infrared spectrograph in the world
Status and milestones

- Hardware and integration completed 01/2009
- Version 0.1 DRS package delivered 06/2009
- ETC ready 03/2009
- First light 03/2009
- Science verification 08/2009
  ➔ 98 proposal submitted by the community !!!!!!!!

- Preparations GTO program started (Total: 200 nights)
  Common ToO/RRM GRB program (20% to 25%) of the total.

  • Instrument release to the community (P84) Oct 2009

  More than 150 proposal submitted UT2 pressure 7.5 !!!!
Science Case: The physical properties of distant galaxies: GRB host and/or field galaxies

Integrated properties (longslit) or maps(IFU)

☑ Velocity field and sigma map
☑ Electronic density
☑ Extinction
☑ Metal content
☑ SFR
☑ Etc ...
Example of science w/ IFUs

HST+3D info + multi-λ

LIRGs: we have integrated properties: metallicity, $A_v$ and SFR(Hα and IR), and maps: color Morph + VF


Maps but small $\Delta \lambda$
Science Case: GRB host galaxies

GRB980525 à $z=0.0086$

$\Delta \lambda$ >> but only integrated properties
Science Case: GRB host galaxies

Argus Observations R ~ 27000

GRB950425

Ha Flux

VF

Metallicity NII/Ha

Large FoV but really small $\Delta \lambda$
Science Case: GRB host galaxies

Argus Observations $R \sim 10000$: new observations from OII to Ha

GRB980525 at $z=0.0086$

Large FoV but really small $\Delta \lambda$
Science Case: GRB host galaxies

And X-Shooter?

- Large wavelength coverage: 300 – 2500 nm
- R ~ 7 000 - 12 000 with 0.6” slit: Direct slit or IFU (image slicer)

Simulations + new tools of analyses

Y. Yang (GEPI) M.Puech (ESO) H. Flores (GEPI)
X-shooter science

Scientific driver for this instrument

- To study the physical origin of gamma-ray bursts and the nature of their host galaxies,
- To study faint brown dwarfs,
- to identify the progenitors of Type Ia supernovae,
- To quantify the properties of high redshift (lensed) galaxies, and
- To probe the structure of the intergalactic medium.
- Identification of sources of which astrophysical nature (or redshift) is not known
- Spectroscopic follow-up of new sources discovered with survey instruments (VST/OmegaCam, VISTA,...)
- Complementary observations (Chandra, XMM, INTEGRAL, ALMA, ...)
X-shooter FOV with IFU (1.4” x 4”) is superposed to the angular distribution of 20 OTs in their galaxy.
X-shooter spectrum of GRB 021004 at z=8.5

T_{exp} = 2 \text{ hr}, \text{ reionization at } z=7, \text{ 7 hours post burst.}

P. Goldoni
And ...

- Spectral properties and gas kinematics of protostars
- Properties of cool white dwarfs
- The nature of neutron stars in close binary systems
- Physical processes in the atmospheres of brown dwarfs
- Properties of core-collapse supernovae; Type Ia supernovae to $z = 1.7$
- Gamma-ray bursts as high-energy laboratories and cosmological probes of the intergalactic medium
- The role of faint emission line galaxies in the redshift interval $z = 1.6-2.6$
- Properties of high mass star formation and massive galaxies at high $z$
- Metal enrichment in the early universe through the study of high $z$ absorption systems
- Tomography of the Intergalactic Medium through the observations of faint background QSOs
On March 15.22 UT we initiated observations of GRB 090313 (Chornock et al., GCNC 8979; Mao et al., GCNC 8980) with X-shooter at the ESO VLT. X-shooter is the first of the second-generation VLT instruments, equipped with three Echelle spectrographs, the Ultraviolet/Blue (UVB), the Visible (VIS) and the Near Infrared (NIR). Combined, they provide a fixed spectral format and cover in one shot the spectral range 3000 - 24000 Å at medium spectral resolution (R = 4000 - 10000 depending on the arm and slit width). The mean epoch of the observation was 45.3 hours after the burst, when the afterglow had faded to R ~ 21.6 (Perley et al. GCNC 9001; Cobb et al. GCNC 9008). In the 4 x 1500 s combined spectrum we clearly detect continuum above 5580 Å with several absorption lines; below this, the signal is dominated by background emission produced by the nearby Moon (90 % illumination at 37 deg from the field). The spectrum indicates an absorption redshift of z = 3.3721 ± 0.0004 (consistent with that measured by Chornock et al., GCNC 8994 and Thoene et al., GCNC 9012) through the detection of Si II (1304.5), C II (1334.5), Si IV (1393.8), Si IV (1402.8), Si II (1526.7), C IV (1548.2,1550.8), Fe II (1608.5), Fe II (1611.2), Al III (1854.7), Al III (1862.8), Zn II (2062.6), Fe II (2600.1), Mg II (2796.3, 2803.5) and Mg I (2853.0). The intervening system identified by Thoene et al. (GCNC 9012) is resolved into multiple components through the detection of Fe II, Mg II and Mg I lines with its main absorption at redshift 1.800. A further system at z = 1.959 shows Fe II, Mg II and Mg I absorption.

The spectra of GRB 090313 will be made public on the ESO web as other data of scientific relevance obtained during the commissioning of the instrument.
GRB 090313: X-shooter’s first shot at a GRB

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