Gamma Ray Bursts: 15 yrs after BeppoSAX

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15 yrs ago (30 April 1996) BeppoSAX was launched with an Atlas-Centaure launcher from Cape Canaveral, FL (USA)
In less than 1 yr from its launch, on 28 Febr 1997, the 30 yr mystery about GRB sites was unveiled: GRBs are huge explosive events in galaxies at cosmological distances.

Why BeppoSAX?

Why so long time for this discovery?
1st Lecture
✓ Pre-BeppoSAX era: open issues and major achievements;
✓ BeppoSAX revolution: Why BeppoSAX?

2nd Lecture
• The major BeppoSAX discoveries after the afterglow one;
• Open issues left by BeppoSAX;
• The major discoveries of the Post-BeppoSAX era;
• Still open issues and prospects.

GRB discovery

• Discovered at the end of the 60’s with the spy American Vela satellites, devoted to monitor compliance with the 1963 “Partial Test Ban Treaty” by the Soviet Union, and other nuclear-capable states.

• Published by R. Klebesadel, I. Strong & R. Olson (1973)
Major issues

- **Major astrophysical problems:**
  - Which are their progenitors? Normal stars? Compact stars (WD, NS, BH)? Comets? Interstellar medium?
  - Which are their sites (Local, Galactic, Extragalactic)? How much power is it involved?

- **Major observational problems:**
  - Accurate localization of the event: a tough task in the gamma-ray energy band, where detectors, mainly based on Compton scattering, give coarse source directions;
  - Search for the GRB counterparts at longer wavelengths (a new born source or an already existing one?)
From GRB discovery to BeppoSAX launch (1996)

• Many satellite missions (mostly American and French-Russian), but small progress:
  - Very rough localizations. The most accurate with IPN after a long time from events.
  - No evidence of counterparts.
  - No idea of the power output.

• The largest effort with BATSE experiment (20-2000 keV, 8 NaI(Tl), full sky) aboard the NASA CGRO satellite (1991-2000).
Major BATSE Results

- Isotropic distribution of GRBs directions (localization uncertainty ranging from 2° to 30°)
- Paucity of weak events with respect to what expected in an euclidean space
- Hints for a cosmological origin of GRBs, but also consistent with a local origin or Galactic halo.
From the 1995 debate at the Baird Auditorium of the Smithsonian museum of Natural History in Washington

• **Bodhan Paczynski**: “At this time, the cosmological distance is strongly favored over the Galactic one, but it is not proven. …At this time we have no clue as to their nature, even though well over a hundred suggestions were published in the scientific journals.”

• **Don Lamb**: “We do not know the distance scale to GRBs. First I describe the recent discovery that many NS have high enough velocities to escape from the Milky Way. These high-velocity NS form a distant, previously unknown Galactic ‘corona’. This corona is isotropic when viewed from the Earth, and consequently, the population of NS in it can easily explain the angular and brightness distribution of the BATSE bursts.”
The BeppoSAX revolution (1997)

- In only 6 months from its operational life time, BeppoSAX allowed to establish that GRBs are huge explosive events in galaxies at cosmological distances.

Why BeppoSAX?
BeppoSAX initial goals (1981)

- Did not include GRBs.

- **Science goals:**
  - Study of celestial X-ray sources in a broad band 0.1-300 keV;
  - 2-30 keV sky monitoring, in particular, of the Galactic plane.
BeppoSAX initial configuration

Payload

- **Narrow Field Instruments:**
  - 4 focusing telescopes
    LECS+MECS (0.2-10 keV), PI G. Boella
  - HPGSPC (4-60 keV), PI G. Manzo
  - PDS (15-200 keV), PI FFrontera (Deputies: ECosta, DDal Fiume)

- **WFCs (2-28 keV, PI R. Jager):**
  - 2 units in opposite directions,
  - proportional counters + coded mask, ang. res. 3’-4’
  - FOV 20°x20° (fwhm)
The Gamma Ray Burst Monitor

- During the phase A study (1983-84), FF proposed to exploit the PDS Anti-Coincidence shield as GRBM:
  - 4 units, CsI (Na) scintillators, 40-700 keV, 4200 cm², almost all sky FOV
  - 2 Units were coaligned with WFCs !!!
- FF expected: 2-3 GRBs/yr detected with GRBM could be localized with WFCs (arcmin accuracy).
- International echo (Hurley 1986)
GRBM development story

- GRBM was approved by SAX Consortium in 1990.
- GRBM design, later developed:
  - A trigger system to identify GRB events
  - 4 electronic chains for getting continuously spectra and ratemeters from each GRBM unit;
  - Gain monitoring;
  - In case of a trigger: high time resolution ratemeters (down to 0.5 ms).
- GRBM prototype developed, also with repeated testing with the SATURNE proton accelerator (Saclay).
- Flight model developed by Laben under the FF supervision.
- Calibration campaign after integration in the satellite at ESTEC (Noordwijk, NL) led by E. Costa.
BeppoSAX launch and phases

• **Launch**, on 30 April 1996 from Cape Canaveral with an Atlas-Centaure rocket;

• **Commissioning phase**: 2 months;

• **Science Verification Phase (SVP)**: July - September 1996;

• **Operational phase**: from October 1996.
• During SVP, several GRBs detected with GRBM were found with off-line analysis.

• In coincidence with one of these (GRB960720), X-ray counterpart was found in WFC data and accurately localized one month after the event.

• A pointing of the NFI s toward the GRB direction, but no X-ray counterpart found.
Following the 960720 experience

• From GRB960720 experience, two alternatives:
  – No X-ray residual radiation at all;
  – A rapidly fading X-ray source.
• A prompt follow up would be the next attack.
• Observation strategy devised:
  – Prompt analysis of the GRBM data and validation of real bursts.
  – WFC data analysis in coincidence with detected GRBs;
  – In the case of a positive detection/localization with WFC, follow-up with NFI s.
• This observation strategy became operative in Jan 1997.
GRB afterglow discovery

- Unsuccessful search of an X-ray counterpart of the first localized GRB: 970111.

- Second GRB promptly identified and well localized occurred on 28 Feb 1997: 970228

- Follow up after 8 hrs: afterglow emission discovered.

Costa, FF+1997
X-ray Afterglow emission properties of GRB970228

Power-law decay and power-law spectrum

\[ F(t) \sim t^{-1.3} \]

Costa, FF+1997

\[ I(E) \sim E^{-2.1} \]

FF, Costa+1998
First discovery of an optical afterglow

The 970228 error box provided by BeppoSAX was at last compatible with a search in optical images within a reasonable small field.

Various teams observed the field at the BeppoSAX coordinates distributed by a telegram to the International Astronomical Union (Costa et.al 1997)

Paul Groot of the team of Ian Van Paradijs was the first to observe twice the field with William Herschel Telescope and to detect the optical afterglow decaying with the same power-law index of X-ray afterglow.

Van Paradjis+ 1997
Improvement of the GRB discovery with ROSAT

- ROSAT was the most sensitive Soft X-ray telescope at the epoch. We requested a TOO pointing in the direction of the burst. Observation performed after 10 days.

\[ FF+1998 \]

The error box shrunked down to 5 arcsec.
The afterglow was observed with HST.

Discovered a decaying point source included within a faint nebulosity, possibly a far galaxy.
## The discovery sequence

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Angular Resolution</th>
<th>Time (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAX - GRBM</td>
<td>several degrees</td>
<td>100 m</td>
</tr>
<tr>
<td>SAX - WFC</td>
<td>5-3 arcmin</td>
<td>3h</td>
</tr>
<tr>
<td>SAX - NFI</td>
<td>1 arcmin</td>
<td>8h</td>
</tr>
<tr>
<td>Optical Telescopes</td>
<td>1 arcsec</td>
<td>2-10d</td>
</tr>
<tr>
<td>Hubble</td>
<td>0.2 arcsec</td>
<td>1 month</td>
</tr>
</tbody>
</table>

- Every improved error box is included in the previous and has a transient object.
- All detected transients decay with the same power-law.
  
  *It is the same object*
First measurement of GRB redshift: GRB970508 ($z = 0.835$, spectroscopic observations with Keck telescope)
First consequences of the redshift measurement

- From the distance we derived the energetics of GRB970508. Assuming isotropy:
  \[ E_{\text{iso}} = (0.61 \pm 0.13) \times 10^{52} \text{ ergs} \]

- On December 14, 1997 the redshift of another BeppoSAX GRB (971214) was determined: \( z = 3.42 \).

- The corresponding energetics was \( E_{\text{iso}} = (2.45 \pm 0.28) \times 10^{53} \text{ ergs} \rightarrow 0.14 \, m_\odot c^2 \)
Discovery of the radio afterglow from GRB970508

- The first radio counterpart of a GRB found with VLA radio-telescope.
- From the observed fluctuations and their time behaviour, microarcsecond size of the emitting source in rapid expansion.

Frail+ 1997
International resonance 1/2

- In the first two years the number of papers citing BeppoSAX (mainly for GRBs) was equivalent to those citing HST.
- ESA modified the data flow of the INTEGRAL satellite in order to allow a prompt localization of GRBs with the on ground analysis of the Gamma-Ray Imager (IBIS) data.
- NASA issued an Announcement of Opportunity for a new medium-size scientific satellite: many missions dedicated to GRBs were submitted and one (SWIFT) selected.
- SWIFT is based on the same “sequence” of BeppoSAX, but the localization and re-pointing are automatically performed in a much shorter time.
The major optical and radio telescopes dedicated observing time to follow up GRBs.

Some of them modified their procedures or their equipment to make these observations faster.

Several optical or NIR telescopes were built with robotic pointing on coordinates distributed by BeppoSAX through the GCN network set up by NASA.

For two years (1997-1999) the GRBs discoveries classified by Science among the top 10 over all the world and over all the science fields.
Some major further BeppoSAX results
Late X-ray afterglow properties

- Detection rate: 90%
- Only ~40% observed in the optical: “dark GRBs”.
- PL photon spectrum ($\propto E^{-\Gamma}$):
  - $<\Gamma>=1.97\pm0.03$
  - $\sigma_{\Gamma} = 0.4$
- Fading behaviour $\propto t^{-\beta}$:
  - $<\beta>=1.30\pm0.02$
  - $\sigma_{\beta} = 0.35$

Spherical expansion
Expanding jet

FF 2003
X-ray spectral properties of the continuum prompt emission

GRB 000528

FF+2004

FF+2000
Transient X-ray absorption lines in the prompt emission

Derived X-ray redshift $z \approx 0.86$, later found consistent with the optical one ($z = 0.8424$, Le-Floc’h+2002)
GRB - Supernovae connection

GRB980425
SN1998bw

Galama+1998

Pian+2000
Pian+2003
Very important for understanding the physics of the GRB emission.

Theoretical consequences of the BeppoSAX discovery
The fireball model

- From the observed properties
  - luminosities up to $10^{55}$ ergs,
  - GRB duration,
  - Non thermal spectra,
  - Short time variability
  - Photon energies >1 MeV

  a fireball in relativistic expansion (Cavallo&Rees78, Guilbert+83, Goodman84, Paczynsky86).

- Notice: the fireball model does not give any information about GRB progenitor.

Fireball scenario:
1. Internal energy converted in bulk kinetic energy due to super-Eddington luminosity;
2. Kinetic energy converted in electromagnetic energy through shocks (internal, external).
Drawbacks of the fireball model

- **Energetics.**
  - From the similar kinetic energy of outflowing shells, a small conversion efficiency (e.g., Daigne+98).
  - Internal shocks can hardly produce the observed radiation.

- **Energy distribution between prompt and afterglow**
  - External shocks should be more efficient;
  - Instead we found more energy released during the prompt emission (confirmed by Swift).
The GRB progenitors

- From energetics, variability time scales, GRB duration likely accretion of a massive accretion disk onto a compact object, likely a BH.
- Many models proposed:
  - Failed SNe (Woosley93);
  - collapsar (Paczynski98);
  - Binary NS or NS-BH merger (Narayan+92);
  - WD-NS merger
  - Fireshell Model (Ruffini+01)
  - Supranova model (Vietri+98)
Issues left open by BeppoSAX

• GRB-supernova connection.
• X-ray afterglow curve at early times.
• Breaks in the X-ray afterglow light curves:
  – are the breaks observed in the optical band achromatic?
• Afterglow of short GRBs.
• GRB environment.
  – Were the X-ray emission lines real?
• Dark GRBs
  – Requested prompt afterglow searches
• Origin of X-ray flashes
• Emission mechanisms at work during the prompt and the afterglow emission.
GRB-Supernova connection

SN2003dh (z=0.1687) GRB030329

Vanderspeck+04

Stanek+03

GRB 030329

-2.5 log(f_\lambda) + Constant

30–400 keV

2–10 keV

Time since Trigger (s)

SN 1998bw at day -7

GRB 030329 Apr 8 UT continuum subtracted

SN 1998bw at max

Observed Wavelength (Å)

Rest Wavelength (Å)
The early afterglow of long GRBs

Gehrels+2009

Two main types of lc:
- Steep to shallow (most frequent);
- Smoothly declining.
- In the 1st case, X-ray flares.

Interpretation:
- Steep decay=tail of the prompt emission;
- Steep to shallow: afterglow dominance;
- Long flatness: continuous energy injection;
- Second break: injection exhaustion
Afterglow of short GRBs and their sites

- Similar features of the long GRB afterglow (even flares);
- Also optical properties are similar to those of long GRBs.
- The $z$ distribution is still an open issue (more statistics).
- Extended soft X-ray emission.

Optical counterpart of GRB050709: the first short GRB optically identified ($z=0.160$)
Circumburst medium

- No X-ray lines during afterglow;
- Significant absorption (in excess of the Galactic one);
- Discrepancy between NH (X) and NH (O);
- A possible explanation (Campana+2010): H photoionization due to the X-ray radiation field.

Campana-2010
Dark GRBs

- Many of the Swift GRBs (25%-40%, depending on definition) are optically "dark" (Greiner+2011).
- Possible explanation:
  - Extinction effect for low $x$ GRBs;
  - distance effect for high $z$ GRBs (>20% of dark GRBs).
XRF origin

- A wealth of information from HETE 2 (20 XRF with known z).
- Likely low luminosity GRBs;
- Properties similar to those of GRBs with lower Ep and higher X-ray flux.
- Lower z distribution than GRB one
- Are more common in the local Universe?
High energy gamma-rays (>100 MeV) from GRBs

- Observed from many GRBs;
- Most spectra consistent with the extension of the lower energy spectrum (>8 keV);
- In some cases, high energy spectra consistent with a MeV BB plus an extra PL;
- Lag time of a few secs.
Some relevant still open issues

- Physics underlying the GRB prompt emission;
- GRB progenitors and circumburst environment;
- Cosmology with GRBs;
- Polarization measurement of the GRB prompt emission:
  - for testing emission mechanism;
  - For testing Loop Quantum Gravity Theories (from the rotation of the polarization angle as a function of the square of the energy and of the distance);
- Physics with GRBs (e.g., test of quantum gravity, transition to quark stars).
Observational Prospects

- In addition to the current operational missions (Swift, Fermi, Agile, ground telescopes):
  - In X-/gamma-rays: SVOM (4 keV-5 MeV)
  - In UHEGR: MAGIC, HESS, VERITAS (~ 1 TeV), CTA (>100 GeV);
  - In Radio: EVLA (10µJy), wide FOV telescopes LOFAR, SKA
  - Neutrinos: AMANDA, IceCube, ANTARES
  - GWs: LIGO, TAMA, VIRGO.
Conclusion

- The discovery of the GRB sites and afterglow with BeppoSAX will continue to push up the frontiers of our knowledge of the Universe for many years.