Unveiling GRB Orphan Afterglows in Rubin LSST data with FINK

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Overview

GRB orphan afterglows

ZTF public data through FINK

Work ahead

Outline

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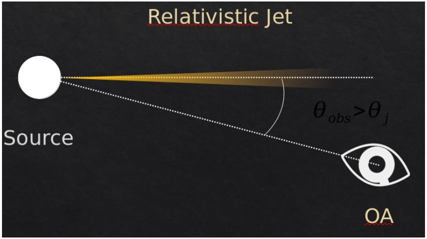
GRB knowledge

- Thousands of GRBs observed in X– and γ–rays, including active optical follow–up observations on–ground
  - Swift and Fermi in space today, SVOM soon
  - *redshift* is important
- Population study through large catalogs: Fermi LAT and GBM, Swift BAT+
- Modeling work on–going for the prompt and afterglow emissions and for the progenitors populations
- But:
  - no single model can explain all observations
  - not all GRBs can be associated to a type of progenitor
  - not sure that all classes of progenitors are known
  - circum–stellar environment seems to show a large variety
  - no good understanding of the jet structure (Lorentz factor, opening angle, geometry, multiple emission zones)
  - each burst still seems different to all the previous ones. . .

Orphan afterglows



GRBs seen off–axis

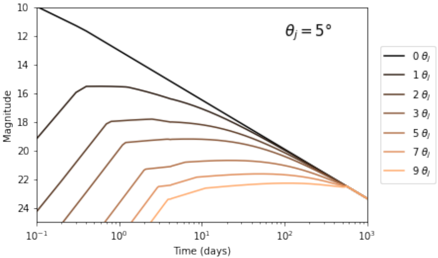
- no γ rays for no jet boost
- $\sim 100\times$ more the number of known GRBs (Ghirlanda 2015)
- should exist if GRBs are relativistic and jetted. . . but none confirmed so far!

– an entire new population of "GRBs" to discover

– extend parameters phase space and complimentary information on:

  - overall geometry and energetic of the system
  - jet structure, choked jets, cocoons
  - progenitor population models

Optical remanence



Afterglow @ 500 nm for different observing angles

Off–axis optical flux

- optical emission peaks later (hours to days)
- but maximum flux is dimmer.

$\Rightarrow$ prime target for Rubin survey

$\Rightarrow$ $\sim$ 50/year (Ghirlanda 2015)

– Preliminary work done by Marina Masson for her M1 internship in Spring 2021
  - Choose a model, code and run simulations
  - Characterize roughly an orphan afterglow (OA) light curve
  - Look for OA–like light curves in ZTF public stream using the FINK science portal

Emission model for the light curves

- Studied a (large) bunch of papers, not always easy to find enough information to be able to implement models in a simple analytic form
- Converged on synchrotron afterglow model based on:
  - Sari, Piran et Narayan 1997 adiabatic case for flux
  - Zou, Wu et Dai 2006 for the viewing angle scaling factor

Sari, Piran et Narayan 1997 (cas adiabatique et phase de refroidissement lent)

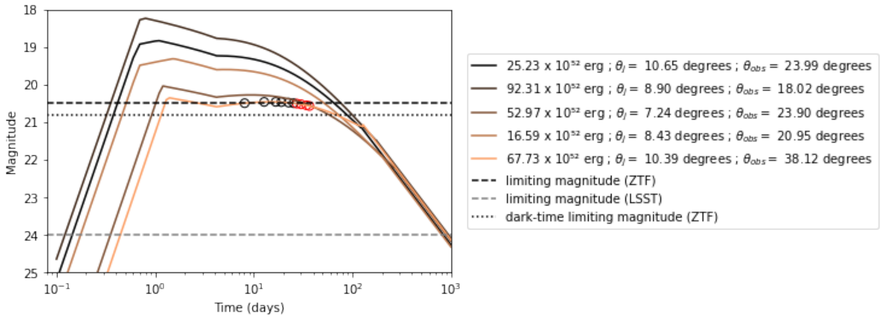
$$F_\nu = \begin{cases} (\nu/\nu_m)^{1/3} F_{\nu,max} & \nu_m > \nu \\ (\nu/\nu_m)^{-(p-1)/2} F_{\nu,max} & \nu_c > \nu > \nu_m \\ (\nu_c/\nu_m)^{-(p-1)/2} (\nu/\nu_c)^{-p/2} F_{\nu,max} & \nu > \nu_c \end{cases}$$

Zou, Wu et Dai 2006

$$F_\nu(\theta_{obs}, t) = a^3 F_{\nu/a}(0, at) \qquad \text{avec } a = \frac{1-\beta}{1-\beta cos\theta_{obs}}$$

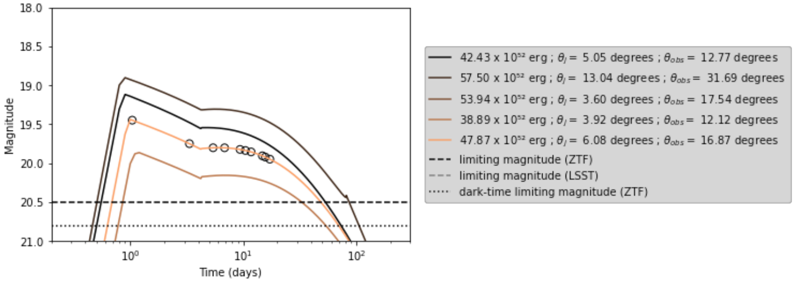
a le facteur d'échelle entre l'intérieur et l'extérieur du jet.

Light curves simulations



- Scanning parameters, looking at light curves
  - total energy from 10^{51}–10^{54} ergs
  - opening angle from $\theta_j \sim 5^\circ$ –15°
  - viewing angle from 2 to $5\times\theta_j$

Light curves characteristics



– Minimal requirements to skim ZTF public data
  - magnitude greater than 18 (dim transients!)
  - $>$ 3 detections in 10 days, and third point at lower flux than the second one
  - $g - r$ color constant and $\sim$ 0.3
  - transient duration is less than a month

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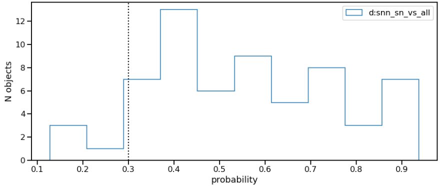
Looking into ZTF public stream

– FINK
  - conservative data extraction by Julien Peloton from the FINK data base
    - Magnitude$>$ 18 and more than 3 detections in 10 days

  $\Rightarrow$ from 80 millions alerts (18 months of data available) to 100 objects per month
  - short list of candidates + REST API to get FINK data on disk for further selections

– Tighter selection
  - remove variable objects ($<$ 30 days)
  - not a supernovae (FINK SN prob$<$ 0.3)

  $\Rightarrow$ a handful of objects to scan through



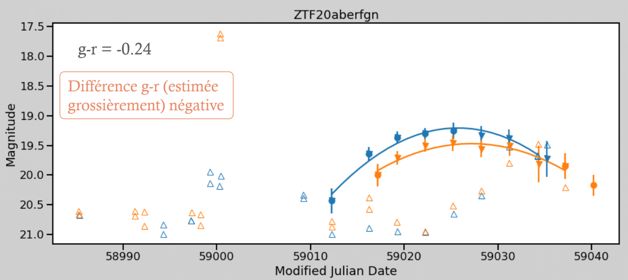
SN probability module distribution

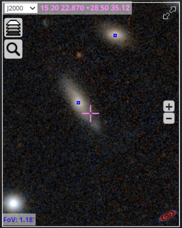
ZTF20aberfgn, in Corona Borealis

ZTF20aberfgn

Coordonnées galactiques :
44.79572262 ° , 57.2073661 °

Détection | Fond connu | Différence





FINK Science Portal

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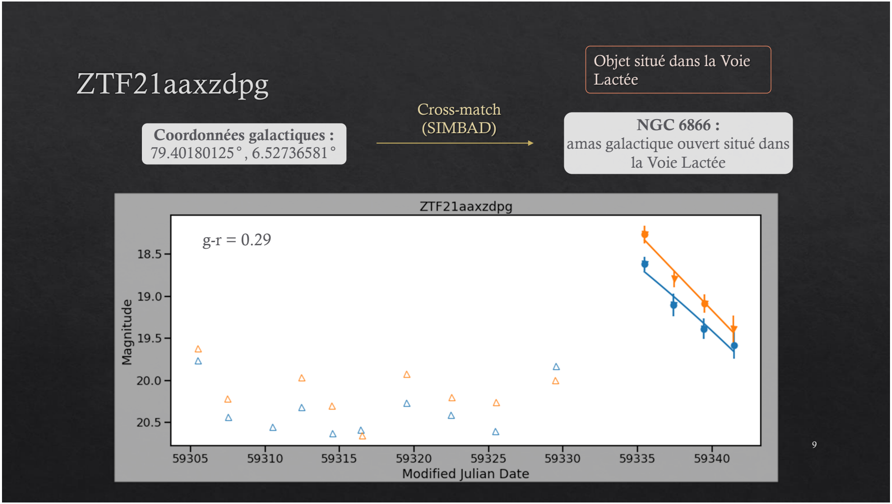
ZTF21aaxzdpg, in Cygnus



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Work ahead (M2 internship spring 2022)

- Work with "real" emission models
  - simulations from different models to understand systematics
  - [github:geoffryan/afterglowpy] is next: see arXiv:1910.11691, van Eerten 2018
- Study population models as well
  - to be able to produce realistic sample of light curves in terms Eiso, jet opening angle, redshift etc. . .
- Run multiple samples of simulations
  - per model class, bracketing parameters, (survey modes)
- Design and implement a new filter in FINK
  - simple cuts, machine learning, active learning, deep learning
  - likely work on a proper "color" module as well
  - started discussion within FINK, with the group working on GRBs (Damien, Manal, . . .)
  - more discussions needed with supernovists !

What to do with the best candidates?

- Multi-wavelength
  - optical, radio, spectroscopy, interfometry, X and gamma!
- Multi–messenger: GW, Neutrino, CR
- Consider excellent space localization but bad time localization (no T_0)
  - still possible to look for sub-threshold signals

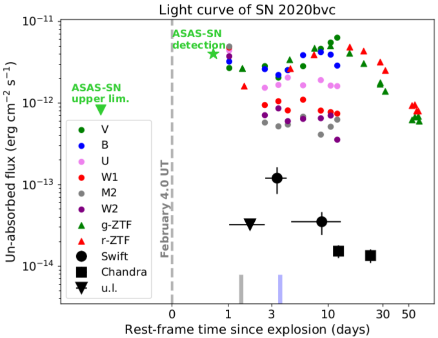
$\rightarrow$ Large data phase space

$\rightarrow$ Need to define the best strategy to be able to confirm that objects are really orphan afterglows

$\Rightarrow$ Work within the Transient Sky (TS2020) initiative

SN2020bvc as an off–axis GRB afterglow

- Long (GRBs) are associated with very energetic, broad-lined supernovae of Type Ic–Broad Lines.
- Some SN Ic-BL not associated with GRBs could actually have an off–axis GRB as inner engine.
  - γ–ray emission is emitted in narrow jets but the SN emission is isotropic.



2020A&A...639L..11I

- X–ray, optical, radio follow–up
- compare with other SN and GRB afterglow model
- disentangle SN and off–axis GRB components
- derive possible GRB date and time, and viewing angle

Non exhaustive list of OA candidates

- **PTF11agg**: *"Discovery of a Cosmological, Relativistic Outburst via its Rapidly Fading Optical Emission"* [2013ApJ...769..130C]
- **ZTF19abvizsw** (AT2019pim): *"Liverpool Telescope observations of ZTF19abvizsw, a candidate untriggered GRB afterglow "*[GCN 25643] and all GCNs associated to [Kool et al., GCN 25616]
- **ZTF20aajnksq** (AT2020blt): *"ZTF20aajnksq (AT 2020blt): A Fast Optical Transient at z $\sim$ 2.9 with No Detected Gamma-Ray Burst Counterpart"* [2020ApJ...905...98H]
- **SN2020bvc**: *"The broad-line type Ic SN 2020bvc: signatures of an off-axis gamma-ray burst afterglow"* [2020A&A...639L..11I]
- **ZTF21aaeyldq** (AT2021any): *"Revealing nature of GRB 210205A, ZTF21aaeyldq (AT2021any), and follow-up observations with the 4K$\times$4K CCD Imager+3.6m DOT"* [Nov. 2021, Journal of Astrophysics and Astronomy]
- But things are not so clear: *"Low–efficiency long gamma–ray bursts: a case study with AT2020BLT"* [2021arXiv210601556S]

Conclusions

- Nice exercise to understand and characterize optical afterglow light curves of off–axis GRBs, a.k.a. orphan afterglows
  - excellent to have FINK and ZTF public data
  - found a couple of interesting candidates
  - Going deeper with M2 internship + PhD thesis in 2022
- Wanderings
  - orphan afterglow models reliability / uncertainties
  - need for "full" Rubin image simulation + stack?
  - possible work on image analysis (specific DIA reprocessing)
- Astrophysics and cosmology implications
  - central engine, emission models, jet structure and geometry . . .
  - progenitor populations
  - star formation rates (up to high redshift)
  - possible probes of the environment up to high redshift

$\Rightarrow$ Need collaboration with GRB and SN experts

Backup

Orphan afterglow detection rates

Table 2. Transient surveys in the optical and X-ray bands.

Survey	FOV (deg^2)	Cadence	F_{lim} (mJy)	Coverage (deg^2 $night^{-1}$)	Lifetime days	R_{OA} (deg^{-2} yr^{-1})	$\langle T \rangle$ days	# OA yr^{-1}
PTF	7.8	1m–5d	1.17×10^{-2}	1000		1.5×10^{-3}	1[0.2–3.8]	1.5
ROTSE–II	3.4	1d	1.17×10^{-1}	450		5.2×10^{-4}	0.4[0.1–1.7]	0.1
CIDA–QUEST	5.4	2d–1yr	4.60×10^{-2}	276		8.0×10^{-4}	0.5[0.1–2.3]	0.1
Palomar–Quest	9.4	0.5h–1d	1.17×10^{-2}	500	2003–2008	1.5×10^{-3}	1[0.2–3.8]	0.8
SDSS–II SS	1.5	2d	2.68×10^{-3}	150	2005–2008	3.2×10^{-3}	1.6[0.4–6.3]	0.8
Catilina	2.5	10m–1yr	4.60×10^{-2}	1200		8.0×10^{-4}	0.6[0.1–2.4]	0.6
SLS	1.0	3d–5yr	5.60×10^{-4}	2	2003–2008	5.2×10^{-3}	2.8[0.8–11]	0.03
SkyMapper	5.7	0.2d–1yr	7.39×10^{-2}	1000	2009–...	6.4×10^{-4}	0.5[0.2–2.0]	0.3
Pan–STARRS1	7.0	3d	7.39×10^{-3}	6000	2009–...	2.0×10^{-3}	1[0.3–4.4]	12
LSST	9.6	3d	4.66×10^{-4}	3300	2022–...	5.1×10^{-3}	3[0.8–11]	50
Gaia	0.5×2	20d	3.00×10^{-2}	2000	2014–2019	10^{-3}	1[0.5–5]	2
ZTF *	42.0	1d	2.00×10^{-2}	22 500	2017–...	1.1×10^{-3}	0.8[0.4–4.8]	20
RASS	3.1	...	4.00×10^{-5}	12 000	6 months	8.0×10^{-4}	1[0.3–4.4]	10
eROSITA	0.8	6 months	2.00×10^{-6}	4320*	4 years	3.0×10^{-3}	2[0.5–6.5]	26

Notes. Ongoing and future surveys are marked in boldface. Parameters of the optical surveys, field of view (FOV), cadence, limiting flux F_{lim}, coverage and lifetime are from the compilation of Rau et al. (2009). The rate of orphan afterglow R_{OA} above the survey limiting flux is obtained through the flux density distribution reported in Fig. 2. The average OA duration above this flux limit $\langle T \rangle$ is derived from Fig. 3 and from the parameters of the linear fits reported in Table 1 (minimum and maximum durations are shown in brackets). The last column shows the number of OAs per year detectable by the reported surveys. For the X-ray the sky coverage is intended for 24 h. (*) See http://www.ptf.caltech.edu/ztf and Bellm (2014).

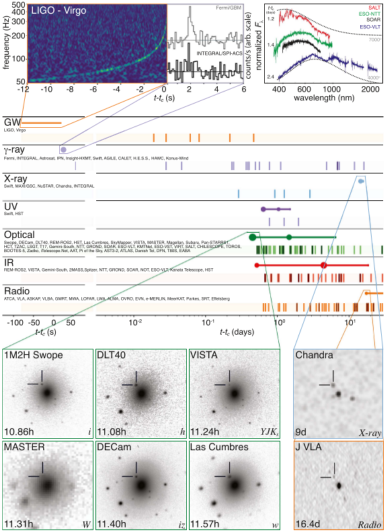
- ZTF of interest already (use public alert stream)
- Rubin LSST is the most promising

More ideas. . .

- Identify ‘optical’ orphan afterglows
  - multi-wavelength data needed for Rubin candidates
  - optical, radio, spectroscopy
- Find origin of some orphan afterglows
  - consider excellent space localization and sub-threshold signals
  - but bad time localization (no T_0)
  - multi–messenger: GW, GRB, CR, Radio, Neutrino

  $\rightarrow$ lots of stuff to do if any signal found
- GRB and progenitors physics
  - need theoretical modeling
  - system geometry, jet structure, star environment, population
  - kilonovae and supernovae
- Cosmology (reionization)
  - population of (Pop III) massive stars as a function of redshift (Long GRBs)

GW 170817



– GW 170817 / GRB 170817A

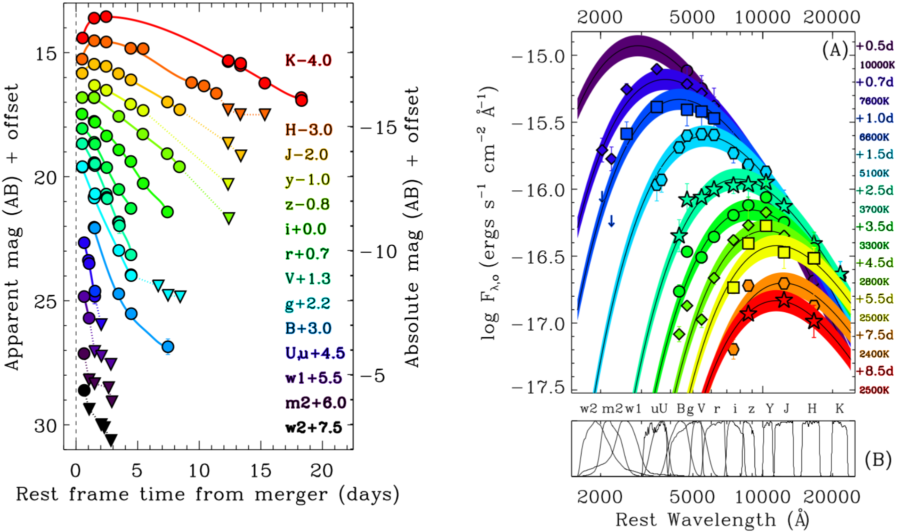
– 70 observatories at different wavelengths and messengers

– long term monitoring on–going

– near threshold GRB for the Fermi–GBM

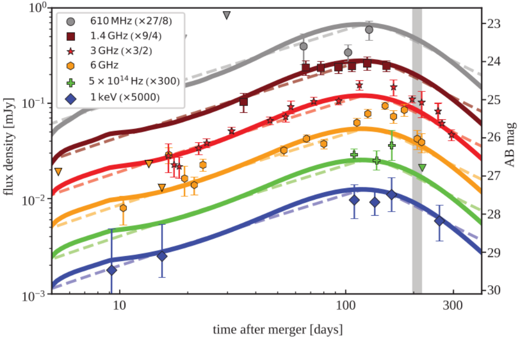
– low total isotropic energy $E_{\rm iso} \sim 10^{47}$ erg

GW 170817 Optical light curves: 20 days



arXiv:1710.05443

GW 170817 4 years afterglow



- Ghirlanda et al 2021, Science
- follow–up observations during the past 4 years
- likely an off–axis successful jet
  - opening angle $\sim 3.5^\circ$
  - viewing angle $\sim 15^\circ$

SN2020bvc spectra

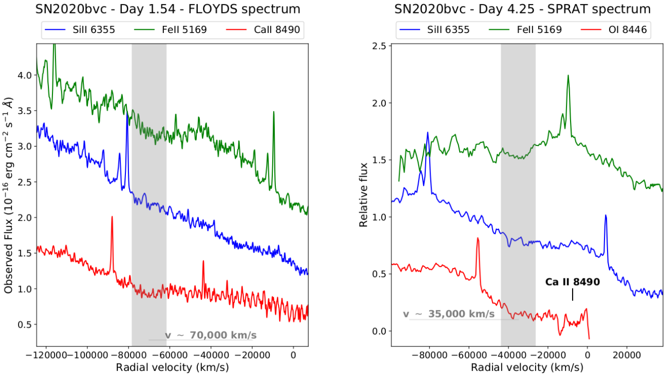


Fig. 3. *(Left panel)* The FLOYDS spectrum of SN 2020bvc observed one day after the SN discovery and centered on three different atomic transitions (Fe II 5169, Si II 6355 and Ca II 8490). The gray band marks the presence of an absorption feature at $v_{exp} \approx 70{,}000$ km/s, common to Fe II and Ca II while it is not observed for Si II. *(Right panel)* The SPRAT spectrum of SN 2020bvc observed three days after the SN discovery. In this panel the red spectrum is centered on the O I 8446 line, with the position of the features indicated for a velocity of $v_{exp} \approx 35{,}000$ km/s, common to Fe II and O I and barely discernible for the Si II line.