Gamma Ray Bursts in the *AstroSat*-CZTI era

A SYNOPSIS

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1 Introduction

Gamma Ray Bursts [GRBs] are the brightest objects in the universe, outshining their parent galaxies by orders of magnitude within only the short duration they last: milliseconds to seconds. They are extragalactic, cosmological, and transient: a GRB never repeats, indicating a violent cataclysmic event. There are two kinds of GRBs: the 'long' GRBs [lGRBs], which last for an order of seconds; and the 'short' GRBs [sGRBs], which last for an order of milliseconds. A lGRB is powered by an ultra-relativistic jet of matter emitted from the environment of a high-mass star collapsing directly into a black hole [BH], while a sGRB is powered from the environment of neutron stars [NS] that merge together to form either a heavier NS, or a BH, releasing the energy initially stored in the high magnetic fields of the merging NSs. The merging NSs also emit gravitational waves that can be observed by earth-based gravitational wave [GW] detectors. The study of the timing, spectroscopy, and polarization of the X-ray photons emitted from the immediate environment of a nascent compact object offers an unique probe to the mysteries of the launching and composition of relativistic jets.

AstroSat is an Indian multi-wavelength satellite, simultaneously observing a wide range of the electromagnetic spectrum: from optical/ultraviolet to X-rays/γ rays. Onboard *AstroSat*, the hard X-ray detector Cadmium Zinc Telluride Imager [CZTI] covers a wide range of energies, from ~ 20 to ~ 400 keV. It has capabilities of: on-axis imaging via the Coded Aperture Mask [CAM]; accurate timing studies of variable sources via time-tagged photon data every $20\,\mu$s; spectroscopy in the wide range of hard X-rays via channel-to-energy conversion of the individual photons; and polarization via the position and energy information of coincident photons detected in neighbouring pixels due to Compton-scattering. Hence it can carry out detailed studies of the prompt emission of GRBs. It complements the capabilities of the softer energy GRB mission *Swift* [15-150 keV] which has an unique capability of following up detected bursts in real-time, and the harder energy GRB mission *Fermi* [8 keV-10 MeV] which can accurately study the evolution of the spectra of the detected bursts.

On the first day of *AstroSat*-CZTI operation, it detected GRB151006A. In view of this, one may ask the following question: What is the rate of GRBs that *AstroSat*-CZTI is supposed to observe in a given time? To answer this, one needs to appreciate the following fact: There is a true all-sky rate of GRBs, accounting for their cosmological rate of formation and any possible intrinsic distribution. A GRB detector samples from this superset, depending on the detector's characteristics: the solid angle of observation, average run time, the energy-band at which it observes, its flux-limit, etc. Hence, if the true cosmological and intrinsic distribution of the population can be theoretically constructed, one should be able to recover the rate of GRB detections for a detector by specifying its characteristics. As a consequence, one would also be able to study the population of both long and short bursts and their cosmological evolution. With the discovery of a sGRB and other electromagnetic counterparts of the gravitational wave [GW] event GW170817, the erstwhile theoretical association of sGRBs with binary neutron star mergers [BNSMs] became an an empirical fact. Thus, the study of the rate of sGRBs can also throw light on the physics of BNSMs. One may similarly ask: What is the rate of the BNSMs that the current and future GW detectors are likely to observe? The answer can be arrived at by studying the intrinsic and cosmological distributions of sGRBs.

Consider the following situation: There exists a population of torches at different distances from the observer. What is the most obvious quantity intrinsic to the torches that determines the observed distribution of the torches? It is their luminosity, denoted by L. The 'luminosity function' [LF] is a probabilistic distribution function over the luminosity of the entire population of GRBs, denoted by Φ. To calculate the expected GRB-detection rate of *AstroSat*, it becomes necessary to construct this detector-independent quantity.

The LF has been studied extensively for galaxies, clusters of galaxies, quasars, white dwarfs, and also more recently for X-ray binaries. The study of the LF of both lGRBs and sGRBs is relatively new, starting off in the last decade. This is due to the fact that the distances to individual GRBs, which are required to extract their intrinsic luminosities from the observed flux, are not accurately measured for the majority of bursts. Significant advances has been made over the decade with the advent of the space-based instrument *Swift*, which has revolutionized the field with quick follow-up observations, enabling the measurement of the redshifts of one-third of the GRB population that it detects. Still, the results in the existing literature clearly point to the lack of strong constraints on the lGRB LF as well the sGRB LF, various authors publishing contradictory claims. This is because of the limitations in the understanding of extremely complex detector characteristics, ill-understood instrumental selection effects, and a relatively small number of redshift-measured GRBs. Other complications, for example the need for the availability of spectral parameters of each individual GRB to correct for the limited bandwidth of the GRB-detectors, plague the field of study.

In my Thesis work, I was first involved in the detailed study of GRB151006A along with the *AstroSat*-CZTI collaboration, where I contributed to the localisation of this off-axis GRB, summarized in Section 2. Then I studied the LF of both long and short GRBs, summarized in Section 3. Using these, I predicted the rate of both long and short bursts observable by *AstroSat*-CZTI, and by comparing with the observed number, demonstrated that the latter falls short by significant percentages. Diagnosing the problem naturally led to a careful study of the definition of 'noise' in the *AstroSat*-CZTI data, and the detection of high energy Cosmic Rays. A revised noise analysis method was shown to improve the sensitivity of detection of weak GRBs by CZTI to the desired performance level. This work is summarized in Section 4.

GRBs are known to be photons released via non-thermal mechanisms like synchrotron emission, by relativistic particles in large-scale collimated jets originating in the environment of nascent NSs or BHs. The angular dependence of the non-thermal emission plays an important role in converting the true cosmological population of GRBs to an observed sample. A theoretical modelling of the angular dependence of synchrotron emission of relativistic jets is carried out, in the regime of the jet being quasi-statically fed by the central engine with fresh relativistic particles. The physics studied here can be extended to model GRBs, by assuming that a GRB pulse is a sum of many such quasi-static phases. The parameters of the model will themselves be functions of time, changing significantly in the time-scale of replenishment. The summary of this work is presented in Section 5.

2 Localisation of off-axis Gamma Ray Bursts

After *AstroSat* was launched on the 28$^{\text{th}}$ September, 2015, CZTI was the first payload to start observing astrophysical sources, on the 6$^{\text{th}}$ October, 2015. On the very same day, it detected a long duration Gamma Ray Burst: GRB151006A [the nomenclature refers to the date of detection by the *Swift* satellite]. The timing and spectroscopy of this GRB using the *AstroSat*-CZTI data was studied, and comparisons were made to the *Swift* and *Fermi* data by other members of the CZTI collaboration. My work demonstrated that CZTI is capable of localizing this off-axis GRB upto around tens of square degrees.

> Using the following inputs, I simulated the expected distribution of photons on the CZTI plane, for different incident angles, binned at $1°$.
>
> - The spectroscopic model fit for GRB151006A, by Vikas Chand of TIFR, Mumbai. This was required to integrate over the energy distribution of the observed GRB, for which the energy was binned in steps of 5 keV over the entire range.
> - A FORTRAN code to simulate the path of photons of given energies [E] incident on CZTI from different angles [θ_x, θ_y in CZTI co-ordinates], written by Professor Dipankar Bhattacharya of the Inter-University Centre for Astronomy and Astrophysics [IUCAA], Pune.

Then I constructed the distribution of photons on the CZTI plane from the data, around the time-interval of the GRB, a total of 60 s. The background subtraction was done by choosing pre and post burst intervals of 90 s and 200 s respectively. This observed distribution was then compared with the expected distribution to deduce that *AstroSat*-CZTI is capable of localizing a GRB of such flux with an error of around tens of square degrees. Although GRBs of higher flux will have smaller uncertainties for a given direction, the variation of the localisation uncertainty with respect to the two angles is not straightforward, because of the complicated structure of the detector.

Finally, using the simulations of photon paths for the expected distribution and independently adding Poisson errors to the simulated distribution, I deduced that the errors in localisation are expected to be only a few square degrees, if the observed errors were indeed Poissonian. This was the motivation of the next project, detailed in Section 4.

> Further details have been reported in Rao et al. (2016).

3 Population studies of Gamma Ray Bursts

From the preliminary analysis of *AstroSat*-CZTI data, it was understood that uncharacterised noise severely hinders the independent detection of GRBs, see Section 2. Hence, all searches for GRBs in *AstroSat*-CZTI were 'triggered searches' – that is, only when GRBs were detected and reported by other satellites, one would manually search these particular GRBs in the CZTI data around the reported time, by running the existing pipeline in a mode different from the normal mode [explained in Section 4]. Thus, without blind-searches, the GRBs that could have been potentially detected by *AstroSat*-CZTI alone, went undetected. It was important to know how many, and this was done by my detailed study of the luminosity function of GRBs.

3.1 Luminosity function of long Gamma Ray Bursts

In this work, I analysed a combined dataset constructed from existing satellites. I justified the use of an alternative method to avoid the instrumental and statistical limitations previously suggested in the literature, demonstrating that it gives statistically reliable results for a large number of lGRBs. Then I placed constraints on the parameters of the lGRB LF, and studied its cosmological evolution.

First I created a common catalogue of GRBs detected by *Swift* and *Fermi*. *Swift* provides measurement of redshifts of one-thirds of the GRB population it detects. On the other hand, *Fermi*, being a wide-band detector, measures the spectral parameters of its detected GRB population accurately. These spectral parameters play an important role in measuring the bolometric flux of the GRBs. Combining these rwo pieces of information, the common catalogue of 66 lGRBs have accurate measurements of the luminosity.

Using this catalogue, the 'Yonetoku correlation' of lGRBs was extensively studied. It was shown that the correlation exhibits a scatter which cannot be explained away by uncertainties alone – contrary to what is claimed by other works in the literature. That is, the scatter is intrinsic to the source population, which prevents the use of lGRBs as distance indicators for the high redshift universe, refuting claims made in the literature. This negates the advantage of GRBs being detected at such cosmological distances. Nevertheless, it was shown that the redshifts generated for lGRBs by assuming the veracity of this correlation can be used in the statistical sense for modelling the LF of lGRBs. It was also shown that the modelling of the spectra of individual lGRBs are not required to carry out the modelling of the LF of a sample of lGRBs, as has been consistently assumed in the literature. Instead, a statistical method was proposed as an alternative, which was first shown to be self-consistent, and then to successfully get around observational selection effects.

Next, via extensive search of the parameter space of the lGRB LF, it was shown that there exists at least one solution for the LF which explains the data for the two missions in three independent redshift bins, that is six independent datasets. This was the first time such a large number of lGRBs were used to model the lGRB LF, hence on its own it is a very important conclusion. Using the established scenario of lGRBs being generated during the collapse of of massive stars into black holes [the 'collapsar' scenario], the fitted lGRB LF models were shown to be consistent with the two most recent works in the literature [wherever comparisons were feasible]. In particular, a cosmological evolution of the LF was confirmed for one of the two models that fit the datasets.

The fitted LF models were then used to calculate the true lGRB rate in the local universe. Finally, they were used to predict the number of lGRBs detectable by *AstroSat*-CZTI, and was tallied with the number derived from the triggered searches carried out in the data by *AstroSat*-CZTI Payload Operation Centre [POC; IUCAA, Pune] members. It was found that a good number of lGRBs were indeed missing, thus highlighting the importance to carry out automated searches for lGRBs in CZTI data. This work predicts that at least ~ 10 high redshift lGRBs are detectable by CZTI per year, and even if 3 of these are uniquely detected by CZTI and followed up automatically in other wavelengths, that will present the current GRB community with an unique opportunity of studying a larger number of high redshift GRBs in their own merit.

> This work was published in Paul (2018a). I had important discussions at crucial junctures of the work with Professor A R Rao. He presented important feedback throughout, as well as read the manuscript before its submission.

This work inspired the work summarized in the next Section, 4. Without the diagnosis of noise in CZTI data and its subsequent prognosis, the automated search of GRBs in the CZTI data cannot be attempted.

3.2 Luminosity function of short Gamma Ray Bursts

The methodology demonstrated in the earlier work [Section 3.1] was extended to the case of sGRBs, with essential modifications. First it was shown that severe selection bias affects the measurement of redshifts of sGRBs, something that was not observed for lGRBs. This rules out all results in the literature that models the sGRB LF by limiting the sample to sGRBs with measured redshifts only. The novel approach of using the 'Yonetoku correlation', which was re-calibrated using the most up-to-date catalogue, was shown to indeed get around this problem.

The sGRB progenitor being binary neutron star mergers [BNSMs] instead of collapsars, the progenitor mass available for GRB-formation must vary differently with redshift than the progenitor mass available for lGRBs. Fortunately, extensive numerical works exist in the field of evolution of stellar populations, which predict this rate by assuming the initial seed mass of the stars in galaxies. Relying on the results of these extensive modelling instead of arbitrary mathematical parametrization as in earlier works, the problem is vastly simplified in the mathematical sense and offers a falsifiable understanding in the physical sense. However, the smaller number of sGRBs available in the existing catalogues creates larger statistical errors in the luminosity distribution thus being modelled. To tackle this, the sGRBs in the *CGRO*-BATSE [*CGRO*: *Compton Gamma Ray Observatory*; BATSE: Burst and Transient Source Experiment] catalogue were also included. This created a further problem: the luminosity distribution for BATSE sGRBs is significantly different from those of *Swift* and *Fermi* sGRBs. This prompted the use of an additional instrument-dependent term while modelling the LF. It was finally possible to conclude that a single physical model of the LF could explain the data of all the three missions successfully, and the instrumental peculiarities were modelled as a by-product.

The fitted LF models were then used to calculate the local as well as the redshift-dependent sGRB rate. The assumption that all BNSMs indeed produce sGRBs, was tested by comparing this rate with the independently measured rate of the BNSMs from the observation of the only BNSM observed till date, GW/EM 170817. Although errors allow the two rates to be mutually consistent, a mild tension was found, which if confirmed with future studies resourced with larger datasets, can confirm the 'cocoon' model proposed by Kasliwal et al. (2017).

Assuming that all BNSMs indeed produce sGRBs, the sGRB rate was extrapolated to predict the rate of BNSMs that can be detected by the gravitational wave [GW] detector networks in their past, present and future observing runs at their designed sensitivities. Consistency of these numbers with the observed rate was demonstrated. According to the predictions, the future of GW detections from BNSMs indeed looks promising, and the amount of computational power and human interpretation of the data required to tackle the future detections may become over-whelming for machines as well as humans.

Finally, the fitted models were used to predict the number of sGRBs detectable by *AstroSat*-CZTI, and tallied against observations. It turns out that the detected numbers are smaller than predicted. A blind search of GRBs in CZTI has the capability of filling up this gap, again inspiring the work summarized in Section 4.

This work was published in Paul (2018b).

3.3 Predictions for future instruments

Athena [Adavanced Telescope for High Energy Astrophysics] is a future European Space Agency mission which will have a soft X-ray telescope called the Wide Field Imager [WFI] with excellent timing characteristics.

In collaboration with Dr. Pragati Pradhan of the Pennsylvania State University [PSU], predictions were made for the detection rate of the future *Athena*-WFI, and compared with old soft X-ray missions, *XMM-Newton* and *Chandra X-ray observatory*.

It was concluded that the number of lGRBs detectable by *Athena*-WFI is 16-20 per year, which is not significantly more than the past two missions. Thus, the futility of trying to do path-breaking science of GRBs by a soft X-ray detector was demonstrated, and the results duly communicated to the leader of the WFI team, Professor David Burrows [PSU].

I also predicted the GRB detection rates of two instruments – one soft X-ray [1-10 keV] and one hard X-ray [20-200 keV] instrument – for a future *AstroSat*-like Indian mission. The predicted numbers are > 200 lGRBs per year for both instruments, ~ 10 sGRBs per year for the soft X-ray detector, and ~ 30 sGRBs per year for the hard X-ray detector. This inspired the inclusion of this capability in the proposal for this mission submitted to the Indian Space Research Organisation [ISRO], by the Principal Investigator of these two instruments, Professor Varun Bhalerao of the Indian Institute of Technology, Bombay [Mumbai, India]. Currently termed *Daksha*, it has been streamlined by the ISRO as a future mission.

4 Detection of high energy Cosmic Rays

As explained in Sections 2, there was a hint of non-Poissonian noise in the CZTI data. That is, systematic noise that were thus far uncharacterised, needed to be understood and eliminated. To verify that this was not a peculiarity of GRB1501006A, the localisation exercise was repeated on a few more long duration GRBs, leading to the same conclusion. Moreover, the absence of detection of a good number of both long and short GRBs by *AstroSat*-CZTI was highlighted in Sections 3.1, and 3.2, and the possible answer to the missing GRBs lay in how the CZTI data was being processed by the CZTI data processing pipeline. Indeed, that was the case. Two tasks in this pipeline, **cztbunchclean** and **cztpixclean**, had been implemented in the satellite verification phase of *AstroSat*, but lacked rigorous understanding or justification. It was imperative to carefully re-examine these tasks and refine them.

As the name suggests, **cztbunchclean** removes 'bunches', defined as time-intervals of $20\,\mu$s [the smallest possible bin] when 3 or more events are registered simultaneously.

Given the empirical background rate of events, it is astrophysically impossible that these events are produced by distinct astrophysical sources; hence they must be correlated. On studying the temporal variation of the 'bunches' whose rate is roughly $70\,\mathrm{s}^{-1}$, and noting the temporal correlation of these events with the charged particle background detected by the Charged Particle Monitor [CPM] on board *AstroSat*, it had been concluded that they are signatures of charged particles bombarding the detector plane. Hence their elimination from the data had been implemented, storing metadata about them in separate files.

First I used the metadata to study whether the bunches themselves show Poissonian behaviour with respect to time, which they should if they are independent from each other. It was seen that such was not always the case, warranting a re-definition of bunches in those special cases. Moreover, by carefully studying the 'bunch-cleaned' data, it was shown that the effect of the bunches remained in the data even after they were removed. The time-scales of both these subtle effects were deduced to be $60\,\mu\mathrm{s}$, pointing to effects of detector electronics. Then a general scheme to eliminate such effects from the data was developed. Consequently it was shown that one could also calibrate the effect of inherent electronic noise in the data to 20%.

Next, I took a re-look at the definition of the 'gross noisy pixels', a very minor subset [~ 100] of all the CZTI pixels [$2^{14} = 16,348$], which misbehave at all times. It was shown that the definition of these pixels and the 'spectroscopically bad pixels', a somewhat larger subset whose calibration parameters had changed drastically after the satellite was flown, were indeed independent. This exercise was necessitated because the identification and elimination of all data from the gross noisy pixels consisted of the first step of **cztpixclean**.

The next step in **cztpixclean** consisted of removing all time-bins in which the rate of observed data was above a defined threshold, the justification being that data from any astrophysically interesting object will never exceed this empirical threshold, hence eliminating only noise in the process. This assumption clearly breaks down in the case of GRBs, because they stand out amongst the data as bright transients. Moreover, removing 'noise' in this manner does not provide any insight into what the noise actually is. To overcome these issues, the CZTI pipeline had always been run with different values of the threshold parameter in the case of GRBs, thus letting through noise that would otherwise be eliminated. This is the diagnosis of the problem that was noticed during the localisation exercise. Naturally, the solution lay in a careful investigation of the data to understand the noise, and execution of a standardized procedure that eliminates systematic noise but leaves GRB photons alone, thus being able to run on all CZTI data with the same set of input parameters.

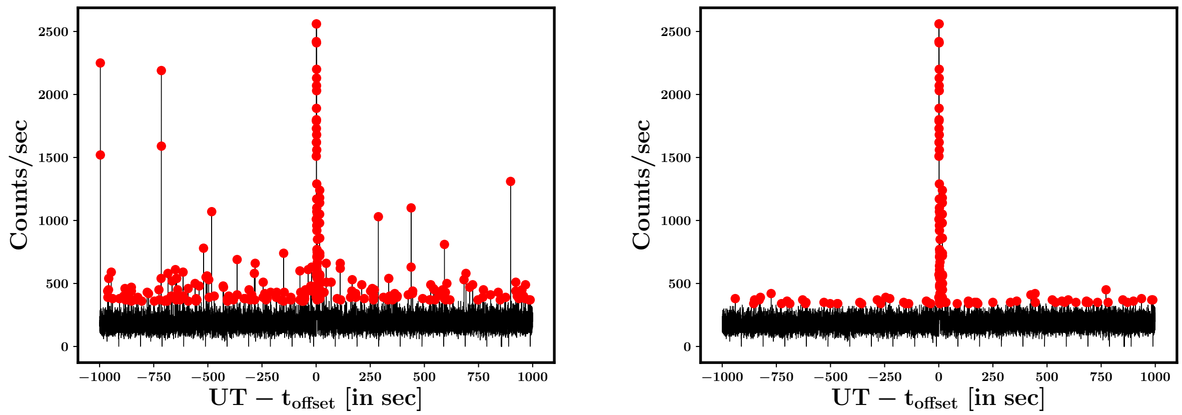

Figure 1: Lightcurves binned at 100 ms before [*Left*] and after [*Right*] **DPHclean** near the bright GRB160802A, red points showing 2σ outliers. Although sudden features in the lightcurve are removed by **DPHclean**, GRB photons are not.

Firstly, I diagnosed the problem by plotting detector plane histograms [DPHs] around all the strong spikes [defined as $> 2\sigma$ deviation from the running median] in the time-series of the data, called the 'lightcurve', binned at 100 ms [see Fig. 1]. Manual investigation of all DPHs helped me understand that other than the time-stamps corresponding to genuine GRBs, all such spikes are created due to clustering of data in a relatively small region of the detector plane, these pixels exhibiting counts much higher than the usual [1 or 2]. These structures are defined as 'DPHstructures'. Then, I developed an algorithm, **DPHclean**, that automatically detects these structures from any DPH, and removes all data that contributes to such spatial clustering from the final output data, see Fig 1. Then the robustness of this algorithm was extensively demonstrated.

The DPHstructures were then studied to understand the reason behind their occurrence, and the detector physics that we could extract from them. For each DPHstructure, I created a detector delay histogram [DDH]: the distribution on the CZTI plane of the delay of the events that contribute to the DPHstructure [from the first event in the structure]. Two kinds of DDHs were noticed: (1) tracks with progressively diminishing delay along a certain direction along the detector; (2) ellipses, with the delay progressively increasing towards the centre of the ellipse. Both these kinds are reminiscent of the DDHs seen in the PICsIT detector on board INTEGRAL, see Segreto et al. 2003. The authors of this paper argue that PICsIT is bombarded with high energy cosmic rays that create these structures by saturating the pixels for ~ 100 ms.

This diagnosis made it immediately clear that the same mechanism was at play for CZTI – the structures were either due to charged particles that themselves leave a track along the detector, or cosmic ray showers originating close to the detector plane giving rise to the ellipses. Although the observed ~ 100 ms time-scale for the evolution of these structures is same for both the instruments, the mechanism cannot be same for CsI and CZT detectors. Hence we identified the only possible explanation to this: the powering circuit of CZTI itself breaks down due to the saturation effect caused by the heavy energy deposition by the charges, and relaxes in that time-scale. The RC time-constant of these circuits are indeed known to be of that order, thus neatly explaining the phenomenon.

By looking at full orbit data, it was proved that bunches and DPHstructures indeed create different numerical effects on the data, and hence, although they are both created by cosmic rays, they are identified by different algorithms. The fact that the rate of bunches [$70\,\mathrm{s}^{-1}$] is much larger than the rate of DPHstructures [$0.245\,\mathrm{s}^{-1}$], leads to the hypothesis that bunches are produced by cosmic rays of lower energy than DPHstructures. This was indeed shown to be correct. By assuming the standard cosmic ray spectrum, and from the knowledge of the rate of these kind of events, upper and lower limits on both these kinds of events were calculated. In fact, the DPHstructures were artificially divided into two kinds [based on the number of events], just to demonstrate this further. It was seen that indeed, there is a continuity of the energy of these three kinds of events.

The details of the initial part of the work were presented as a collaboration report to the *AstroSat*-CZTI group in November 2016, from when Ajay Ratheesh, erstwhile JRF in TIFR, Mumbai, took over for a year to examine the proposed idea. The idea could not be disproved in the course of 2017, and I followed it up again, the final form of which will be reported in Paul et al. [2019, Experimental Astronomy]. The manuscript of this paper is currently under scrutiny by other members of the collaboration.

5 Partially self-absorbed synchrotron jets

Double-lobed radio sources were discovered in the late 1960s via imaging carried out by radio telescopes. With the advent of very long baseline interferometry [VLBI] in the subsequent decades, highly resolved imaging helped interpret them as extragalactic relativistic jets. In the early 1990s, 'Microquasars' were discovered: highly collimated relativistic ejecta of matter from the neighbourhood of a compact object, in most cases a black hole accreting matter from its surroundings.

The earliest theoretical studies to explain the observed properties of relativistic jets identified the observed electromagnetic radiation to be non-thermal emission from the relativistic particles in the jet, specifically synchrotron radiation in the presence of magnetic fields of the black hole environment. In the Blandford & Königl 1979 model [BK model], it is proposed that a steady jet fed by a central engine powers the radio emission, whereas the variability in the observed flux are produced behind strong shocks that either transmit along the jet or are produced at the termination of the jets.

In Microquasars such as GRS 1915+105 and Cygnus X-3, VLBI images have shown evidence of discrete blobs moving away from a central source at apparent superluminal speeds. In the case of Microquasars like Cygnus X-1, the jet appears to be steady over time-scales of a few days. This might be attributed to the steady replenishment of fresh relativistic particles by the 'central engine' driving the jet.

In this work, the findings of the BK model are revisited. Specifically, the dependence of the observed flux from steadily replenished synchrotron jets on their Doppler-factor [δ_j] and viewing angle [i] are investigated, dependencies that were not considered originally. The limitation in the case of conical jets being viewed from the side in the comoving frame of reference, is also addressed here.

The jet viewing angle, i.e. the inclination of the jet viewing axis with the observer's line of sight, is written as i in the observer's frame, and i' in the jet comoving frame. The conservation of photon momentum in a direction perpendicular to the relative motion between the two frames gives $\sin i' = \delta_j \sin i$.

Three limiting analytical approximations are considered. In all the limiting cases, an analytical solution of the radiative transfer equation integrated over the relevant jet cross section is found, to finally give the observed flux in the observer's frame depending on the parameters of the model. In one [the one which is usually assumed], the jet is viewed sideways in the comoving frame. This approximation implies that the observed flux becomes null when the jet is viewed on-axis, e.g. T. V. Cawthorne's article in Hughes (1991). It is pointed out that the above approximation breaks down in the regime where the viewing angle is small, since the jet is no longer viewed sideways in the comoving frame. Another limiting case is of the jet viewed on-axis. The emission is found to be rather strong, corresponding to the global maximum of the flux as a function of the viewing angle. The third approximation is that of the co-moving frame jet viewing angle to be $i' \sim 180°$. This regime corresponds to the viewing angles of $i \gg 1/\Gamma_j$, when the jet bulk Lorentz factor [Γ_j] is large. This case also corresponds to the counterjet emission in the case of $i \simeq 0$.

Using the expressions for the observed flux for the different approximations, a formula is derived for the jet-to-counterjet flux ratio, R, which is then be used to express the speed of the jet, β_j, as

$$\beta_j = \frac{1}{\cos i}\frac{R^{\frac{p+4}{3p+7}} - 1}{R^{\frac{p+4}{3p+7}} + 1}, \tag{1}$$

where p is the index of power-law of the electron number distribution, a parameter of the model. In Zdziarski et al. 2014, since β_j and p are assumed to be independent, the numerical scheme presented there may be revised taking this into consideration. The derived formula is then applied to the black-hole binary Cygnus X-1. Given the jet-to-counterjet flux ratio of $\gtrsim 50$ found observationally by Stirling et al. 2001 and the current estimate of the inclination of $i \simeq 29^{+5^\circ}_{-4}$ by Ziółkowski 2014, it is found that $\beta_j \gtrsim 0.8$, $\Gamma_j \gtrsim 1.6$.

It is also pointed out that when the projection effect is taken into account, the radio observations imply the jet half-opening angle of $\theta_j \lesssim 1^\circ$, a half of the value given by Stirling et al. 2001. If Γ_j is not much above the counterjet limit, the opening angle is $\theta_j \ll 1/\Gamma_j$, and much lower than the values typically observed in Blazars. This means that Blazar jets are less collimated than the steady jet of the Microquasar Cygnus X-1. Blazars are known to be intrinsically variable, the variability timescale itself depending upon the wavelengths, thus complicating their study. If the emission at any wavelength range is found to be quasi-steady, then the flux formula derived here for the on-axis case are directly applicable for them.

> This work was carried out by me under the guidance of Professor Andrzej A Zdziarski, Centrum Astronomiczne im. M. Kopernika, Warszawa, Poland, and was published in Zdziarski, Paul, Osborne, Rao (2016). In the Appendix of this paper, the numerical generalization of the flux formulae for all angles, carried out by Ruaraidh Osborne of the University of Glasgow, was reported.

6 Conclusions

Studying Gamma Ray Bursts can help improve our understanding of the launching of relativistic jets from the neighbourhood of compact objects like black holes and neutron stars. A number of questions arise while studying GRBs with any detector sensitive to them. In a collaborative effort with the *AstroSat*-CZTI team, I characterised the off-axis localisation capability of CZTI with the help of GRB151006A, demonstrating that uncharacterised, systematic noise present in the data affects the detailed studies of GRBs with CZTI. By studying the luminosity function of both long and short GRBs, I modelled the true cosmological rates of both these classes. Using these models, I predicted the rate of

GRBs observable by *AstroSat*-CZTI, as well as other future GRB missions. Having firmly demonstrated that the number of GRBs detected by *AstroSat*-CZTI falls short from the minimally predicted rate, I diagnosed the problem by carefully studying long durations of CZTI data. I showed that the presence of high energy Cosmic Rays thus far unreported was the cause of systematic noise in the CZTI data. I developed an automated algorithm to detect these Cosmic Ray events, the integration of which to the CZTI data processing pipeline is now being implemented. It will enable the process of automatic detection of GRBs by *AstroSat*-CZTI, especially short GRBs. It is envisaged that this will make CZTI a major player in the new era of multi-messenger astronomy, in line with my prediction of detection at least 2 binary neutron star mergers per year from the next observing runs of the global gravitational wave detector network.

A theoretical study of the anisotropy pattern of the synchrotron emission of partially self-absorbed relativistic jets, under the assumption that the jet is constantly energised by a fresh set of particles, is directly applied to the relativistic quasi-static jet in the Microquasar Cygnus X-1. The model studied here is generic, and can be applied to any energy-scales, including GRBs, by assuming that an observed GRB pulse is a sum of many such quasi-static phases.

Thesis related publications in refereed journals

1. **Paul, D.**; MNRAS, 477, 4275; 2018; Binary neutron star merger rate via the luminosity function of short gamma-ray bursts.

2. **Paul, D.**; MNRAS, 473, 3385; 2018; Modelling the luminosity function of long gamma-ray bursts using *Swift* and *Fermi*.

3. Rao et al.; 2016; ApJ, 833, 86; *AstroSat* CZT Imager Observations of GRB151006A: Timing, Spectroscopy, and Polarization Study.

4. Zdziarski, **Paul**, Osborne, Rao; 2016; MNRAS, 463, 1153; Anisotropy of partially self-absorbed jets and the jet of Cyg X-1.

Thesis related publications in preparation

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