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On the Energetics of a Possible Relativistic Jet Associated with the Binary Neutron Star Merger Candidate S190425z

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Abstract

Advanced LIGO and Virgo (AdvLIGO/VIRGO) detectors reported the first binary neutron star merger candidate in the third observing run, S190425z , on 2019 April 25. A weak γ-ray excess was reported nearly coincidentally by the *INTErnational Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) satellite, which accidentally covered the entire localization region of AdvLIGO/VIRGO. Electromagnetic follow-up in longer wavelengths has not lead to the detection of any associated counterparts. Here we combine the available information from gravitational wave measurements and upper limits of fluence from *INTEGRAL* to show that the observations are completely consistent with a relativistic Gaussian structured jet and a typical short duration gamma-ray burst (GRB) being produced in the merger. We obtain posterior bounds on the on-axis isotropic equivalent energy of the associated GRB under different prior distributions. This study demonstrates that even limited gravitational wave and electromagnetic information could be combined to produce valuable insights about outflows from mergers. Future follow-ups may help constrain the jet structure further, especially if there is an orphan afterglow detection associated with the candidate.

Unified Astronomy Thesaurus concepts: Gravitational wave sources (677)

1. Introduction

The joint detection of GW170817 (Abbott et al. 2017b) and GRB 170817A (Abbott et al. 2017a) established the long standing hypothesis that short gamma-ray bursts (GRBs) are powered by binary neutron star (BNS) mergers (Narayan et al. 1992). However, GRB 170817A was several orders of magnitude fainter than its cosmological counterparts (Goldstein et al. 2017b). This led to a proposition that jets need not successfully emerge from some, if not all, BNS mergers and the low-energy γ-ray emission and the nonthermal afterglow could be the result of a subrelativistic cocoon originating from the tidally ejected merger debris (Hallinan et al. 2017; Kasliwal et al. 2017; Gottlieb et al. 2018). However, late very long baseline interferometry observations of GRB 170817A provided strong evidence for the relativistic nature of the outflow (Mooley et al. 2018; Ghirlanda et al. 2019). In addition, temporal evolution of broadband afterglow emission showed excellent agreement with emission from a relativistic jet with an angular structure in energy and velocity (Lazzati et al. 2018; D'Avanzo et al. 2018; Lyman et al. 2018; Margutti et al. 2018; Resmi et al. 2018; Lamb et al. 2019). The low inferred energy of GRB 170817A could be successfully explained by structured relativistic jet models (Kathirgamaraju et al. 2018; Resmi et al. 2018). Numerical simulations of the relativistic jet piercing through the merger ejecta have shown that it successfully emerges with an angular structure (Xie et al. 2018; Geng et al. 2019; Kathirgamaraju et al. 2019). Yet, the possibility of the γ-ray emission from GRB 170817A being intrinsically faint and resulting from a cocoon shock breakout can still be debated (Bromberg et al. 2018; Harrison et al. 2018).

Future multimessenger observations of BNS mergers would help us answer several open questions related to the phenomenon which include: do all the BNS mergers produce relativistic jets and short GRBs similar to the cosmological sample? If not what are the factors that determine the relative fraction between the population that successfully launches a jet and the one that does not? Ongoing and future observing runs of advanced LIGO and Virgo interferometers hence play a central role in deeply understanding the phenomenon of BNS mergers and short GRBs.

The third observing run of LIGO and Virgo gravitational wave interferometers reported the first BNS merger candidate S190425z on 2019 April 25 (LIGO & Collaborations 2019a, Abbott et al. 2020) by the real-time processing of the data using the GstLAL (Messick et al. 2017) and PyCBC Live (Nitz et al. 2018) analysis pipelines. This candidate, which was coincident in the LIGO Livingston and Virgo interferometers, has a false alarm rate of 4.5×10^{-13} Hz (about one in 10^5 yr) from the online analysis and a probability of BNS to be $\geqslant$99%. The preliminary estimate of the luminosity distance to the source is 156 ± 41 Mpc (LIGO & Collaborations 2019b). The 90% sky localization corresponds to 7641 Sq degrees.

Unlike GW170817, the poor sky localization hampered extensive electromagnetic follow-up efforts of S190425z. However, the *INTErnational Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) serendipitously observed the entire localization region of the AdvLIGO/VIRGO simultaneous to S190425z , and found a low signal-to-noise (S/N) short duration ($\sim$1 s) excess 6 s after the merger (Martin-Carillo et al. 2019). Since *INTEGRAL* cannot provide a localization of this excess, and since no other confident EM counterpart is discovered to date, the spatial coincidence of the BNS merger and the *INTEGRAL* source cannot be firmly established. Nevertheless, as the entire localization region of AdvLIGO/VIRGO is covered by the satellite, these observations to the least provide an upper limit to the fluence of any γ-ray signal associated with the merger. The Gamma-ray Burst Monitor (GBM) on board *Fermi* provided flux upper limits for a part of the LIGO/VIRGO localization region (Fletcher et al. 2019). Song et al. (2019) obtained the constraints on the viewing angle of the jet from *Fermi* observations to be between >0.11–0.41 radians, assuming the GW170817 jet to be quasi-universal. In this paper, we ask whether the *INTEGRAL* observations of S190425z are consistent with a relativistic jet associated with this BNS candidate. We combine two observational inputs: the luminosity distance from gravitational waves and the *INTEGRAL* observations (considered both as upper limit and detection), along with a Gaussian structured jet model parametrized by the energy, core angle, and bulk velocity. As there are no constraints on the inclination angle ι (the same as an observer's viewing angle θ_v when the binary orbit is not precessing due to spins) of the binary from the gravitational wave observations yet, we use a simulated population of BNS mergers and use the luminosity distance estimate from GWs together with some conservative S/N limits to obtain a two-dimensional constraint in the $\iota - D_L$ plane (M. Saleem 2020, in preparation; see also Schutz 2011 and Seto 2015 for an analytical treatment of the problem).

Our results show that S190425z could have produced a successful relativistic jet and the prompt gamma-ray emission could well have been missed due to relativistic de-boost. We can derive moderate constraints, though sensitive to the prior used, on the on-axis isotropic equivalent energy of the associated GRB (or on the total energy emitted in γ-rays, while constraints on other parameters are weak. However, the conclusion that the presence of a structured jet is completely consistent with the observations itself is interesting and will help us in future to study the statistical properties of BNS mergers with poor source localization.

The remainder of the paper is organized as follows. Section 2 details the input from gravitational wave observations which goes in as prior information in the analysis of S190425z, reported in Section 3, using a structured jet model. Section 4 discusses the implications of our findings.

2. Constraints from LIGO–Virgo Observations

Even before the discovery of GW170817, it has been argued that multimessenger observations of BNS mergers—especially the measurement of luminosity distance and inclination angle—can have profound implications for the modeling of the associated GRB jet (Arun et al. 2014; Saleem et al. 2018). This is because the jets in the case of BNS mergers are very likely to be launched along the orbital angular momentum axis of the binary, which hence relates the inclination angle with the viewing angle of the jet. The distance and inclination angle in the gravitational waveforms are strongly correlated as they both appear in the amplitude of the gravitational wave signal (Cutler & Flanagan 1994). Hence, it is ideal to obtain the two-dimensional constraints on them using the available information and then use that to model the γ-ray emission.

We use the following information about the BNS candidate S190425z, which is available from the Gamma-ray Coordinates Network (LIGO & Collaborations 2019a, 2019b):

1. It has a probability >99% of being a BNS merger.
2. It was observed by the network of LIGO Livingston (L1) and Virgo (V1) detectors and since the S/N at Virgo was below the threshold, the candidate is considered as a single-detector trigger.
3. The preliminary luminosity distance estimate is given by $D_L = 155 \pm 41$ Mpc.

Using the above inputs, we obtain constraints on the 2D $D_L - \iota$ space as follows. We simulate a population of BNS mergers uniformly distributed in the comoving volume with

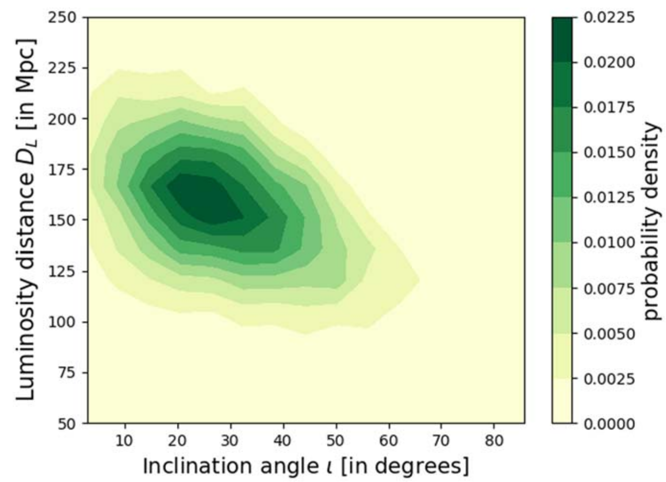

Figure 1. Constraints on the $D_L - \iota$ combination obtained from the observed properties of S190425z as reported in LIGO & Collaborations (2019b).

cos ι of the binaries being distributed uniformly between −1 and 1. The NS masses are uniformly distributed between 1 and $2M_\odot$. We then compute the optimal S/N for each one of them using the restricted post-Newtonian waveform (Cutler & Flanagan 1994). As the trigger is an L1 single-detector trigger, we assume S/N < 4 at V1, following the single-detector threshold considered by GstLAL pipeline and the L1–V1 network S/N > 9, which is motivated by the fact that the network S/N of all the O1/O2 events were above >9 (Abbott et al. 2019). To compute the S/Ns in L1 and V1, we used the best reported O2 sensitivities (Abbott et al. 2019) of L1 and V1 as their representative (conservative) O3 sensitivities (see M. Saleem 2020, in preparation, for more details). From this, we extract a subpopulation of mergers for which the luminosity distance distribution follows a Gaussian distribution consistent with LIGO & Collaborations (2019b). The 2D distribution of $D_L - \iota$ of this subpopulation is shown in Figure 1, which we use as the prior for studying the prompt emission from a short GRB associated with S190425z.

3. Constraining the Jet Properties

In this section, we examine whether the *INTEGRAL* observations are consistent with the BNS merger launching a structured relativistic jet similar to what is seen in GRB 170817A (Lamb & Kobayashi 2017; Resmi et al. 2018; Lamb et al. 2019).

Martin-Carillo et al. (2019) have reported a marginal (3.7 sigma) excess in *INTEGRAL* SPI-ACS counts temporally coincident (+6 s) with the GW trigger. Such a delay can be accounted within different models of jet ejection and γ-ray emission (Zhang et al. 2018), hence it can very likely be associated with the BNS merger candidate. However, we treated this observation as two different possibilities. First, we considered the fluence reported in Minaev et al. (2019), $(1.6 \pm 0.4) \times 10^{-7}$ erg cm^{-2}, as a detection of the associated short GRB. However, since this is a low confidence signal, and also since its spatial coincidence to the BNS merger cannot be established, we considered 2×10^{-7} erg cm^{-2} as a conservative 3σ upper limit to the GRB fluence. For a ~1 s duration signal, this number is also consistent with the position dependent sensitivity map for the duration of the GW candidate released by the *INTEGRAL* collaboration (Savchenko et al. 2019), where the

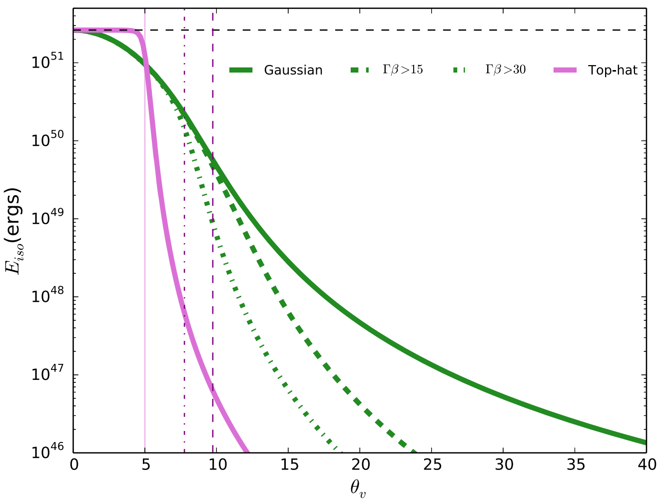

Figure 2. Variation of the isotropic equivalent energy for observers at different viewing angles, for both top-hat (violet curve) and Gaussian (green curves) jets. For both jets, we assumed $E_{\mathrm{tot},\gamma} = 10^{49}$ erg. Both the half-opening angle of the top-hat jet and the core angle of the structured jet are 5°. The bulk Lorentz factor at the axis of the Gaussian jet is same as the bulk Lorentz factor of the top-hat jet, 100. Horizontal dashed black line shows $E_{\mathrm{tot},\gamma}/(1 - \cos(5°)$, the on-axis E_{iso}. For the green solid curve the entire jet is assumed to emit γ-rays, while for the dashed and the dashed–dotted green curves, the emission is restricted to a Γ of 15 (leading to a limit of $\theta = 9\overset{\circ}{.}74$, vertical dashed line) in the integration and 30 (leading to a limit of $7\overset{\circ}{.}76$, vertical dashed–dotted line) respectively.

fluence sensitivity ranges from (1.5–6) $\times$ 10^{-7} erg cm^{-2} s^{-1}. Since the *Fermi* GBM has only seen about 55% of the LIGO error circle (Fletcher et al. 2019), we consider *INTEGRAL* observations in the rest of this paper.

Next, we computed the expected fluence from an underlying relativistic jet. The jet velocity (β) and energy have an angular structure. The bulk Lorentz factor (Γ) distribution across the polar angle θ is given by $\Gamma\beta(\theta) = \Gamma_0\beta_0 \exp\frac{-\theta^2}{2\theta_c^2}$, where θ_c is the jet structure parameter that determines the core of the structured jet. The normalized energy profile function is given by $\epsilon(\theta) \propto \exp\frac{-\theta^2}{\theta_c^2}$, with the normalization constant estimated by $2\pi\int d(\cos\theta)\epsilon(\theta) = 1$. The assumed angular profile of energy and Lorentz factor are motivated by the afterglow of GRB 170817A, where modeling studies have inferred such an angular profile for the outflow kinetic energy and bulk Lorentz factor (Granot et al. 2018; Lazzati et al. 2018; Resmi et al. 2018; Lamb et al. 2019). However, before extending the inferred angular profile of kinetic energy to the energy emitted in γ-rays, it must be noted that the γ-ray efficiency could have its own dependence on latitude, or the γ-ray emission mechanism could be suppressed for jet elements having low bulk Lorentz factors. We discuss these issues later.

Following the framework developed independently by Donaghy (2006) and Salafia et al. (2015), the isotropic equivalent energy measured by an observer at a viewing angle θ_v is

$$E_{\mathrm{iso}}(\theta_v) = \frac{E_{\mathrm{tot},\gamma}}{2\pi}\int_0^{2\pi} d\phi \int_0^{\theta_{\max}} d\theta \sin(\theta) \times \frac{\epsilon(\theta)}{\Gamma(\theta)^4\,[1 - \beta(\theta)\cos\alpha_v]^3}, \quad (1)$$

where $E_{\mathrm{tot},\gamma}$ is the total energy emitted in γ-rays, α_v is the angle between the the line of sight and the direction to a jet element at (θ, ϕ), given by $\cos(\alpha_v) = \cos(\theta_v)\cos(\theta) + \sin(\theta_v)\sin(\theta)\cos(\phi)$, and $\theta_{\max}$ is the upper cutoff of integration over the polar angle of the jet. Such an upper cutoff could arise in two ways, either as the edge of the jet or as a limiting angle where the Lorentz factor or γ-ray emission efficiency drops below a certain threshold value. We numerically integrate Equation (1) to estimate the fluence measured from the structured jet by an off-axis observer as $E_{\mathrm{iso}}(\theta_v)/4\pi d_L^2$.

Essentially, here the energy per solid angle is integrated over the jet surface after accommodating relativistic effects due to viewing angle. Therefore, this method cannot reproduce time or frequency resolved quantities, such as the temporal or spectral peak in a GRB (Salafia et al. 2015).

In Figure 2, we show the behavior of E_{iso} as a function of θ_v for both top-hat and Gaussian structured jets for $E_{\mathrm{tot},\gamma} = 10^{49}$ erg. The bulk Lorentz factor of the top-hat jet, and that at the axis (Γ_0) for the Gaussian jet, are 100. We assumed a core angle of 5° for the Gaussian jet, and the same value is assumed to be the jet half-opening angle θ_j for the top-hat jet. We can see from the figure that on-axis isotropic equivalent energy for a Gaussian structured jet has the same form as that of the top-hat jet with θ_c replaced by θ_j (see Mohan et al. 2019 for an analytical derivation of this), i.e., $E_{\mathrm{iso}}(\theta_v = 0) = E_{\mathrm{tot},\gamma}/[1 - \cos(\theta_c)]$. Therefore, Equation (1) can be rewritten in terms of $E_{\mathrm{iso}}(0)$, the isotropic equivalent energy an on-axis observer would measure. And in Section 4, we present the results in terms of $E_{\mathrm{iso}}(0)$.

In Figure 2, we also show how the isotropic equivalent energy (or fluence) changes for off-axis observers if a cutoff Γ is assumed for efficient γ-ray production in the jet. To begin with, there are not many strong observational or theoretical evidences for such a cutoff in the Lorentz factor below which γ-ray production mechanism stops. In one example, for the low energetic GRB 980425, Lithwick & Sari (2001) has found from optical depth arguments that a bulk Lorentz factor as low as 6.4 is also consistent with the data. On the other hand, there are claims for a possible cutoff at relatively large Lorentz factors ($\Gamma \sim 50$) in long GRBs, estimated through statistical properties of prompt and afterglow emission (Beniamini & Nakar 2019). It is not clear if this is applicable to short GRBs, where a structure in energy and bulk velocity can be developed as the jet propagates through the merger ejecta (Xie et al. 2018; Geng et al. 2019; Kathirgamaraju et al. 2019). Therefore, we arbitrarily assumed various cutoff Lorentz factors to see how that affects an off-axis observer. The solid green curve assumes emission from the entire jet ($\theta_{\max} = \pi/2$), while the dashed green curve assumes a cutoff Lorentz factor $\Gamma_{\mathrm{cut}} = 15$ and the dashed–dotted green curve assumes $\Gamma_{\mathrm{cut}} = 30$. We can see that such a cutoff affects the detection at extreme viewing angles. According to the angular profile of the Lorentz factor we use, if $\Gamma_{\mathrm{cut}} = \Gamma(0)/\sqrt{e}$, the emission will be restricted up to the core angle, and the Gaussian jet will behave more or less the same way as a top-hat jet except for a gradual decrease in fluence for $\theta_v < \theta_c$ instead of the flat profile of the top-hat jet.

In order to better understand the constraints on a possible structured Gaussian jet, we ran a Monte-Carlo simulation with 10^5 realizations of the jet and compared the model fluence with what is observed by *INTEGRAL*. First, we used a uniform distribution in log space, ranging from $44 < \log_{10}(E_{\mathrm{tot},\gamma}/\mathrm{erg})) < 51$ for $E_{\mathrm{tot},\gamma}$. A uniform prior of $3° < \theta_c < 20°$ is considered for the jet core angle. With these values, we were able to cover the entire range of E_{iso} (0) values

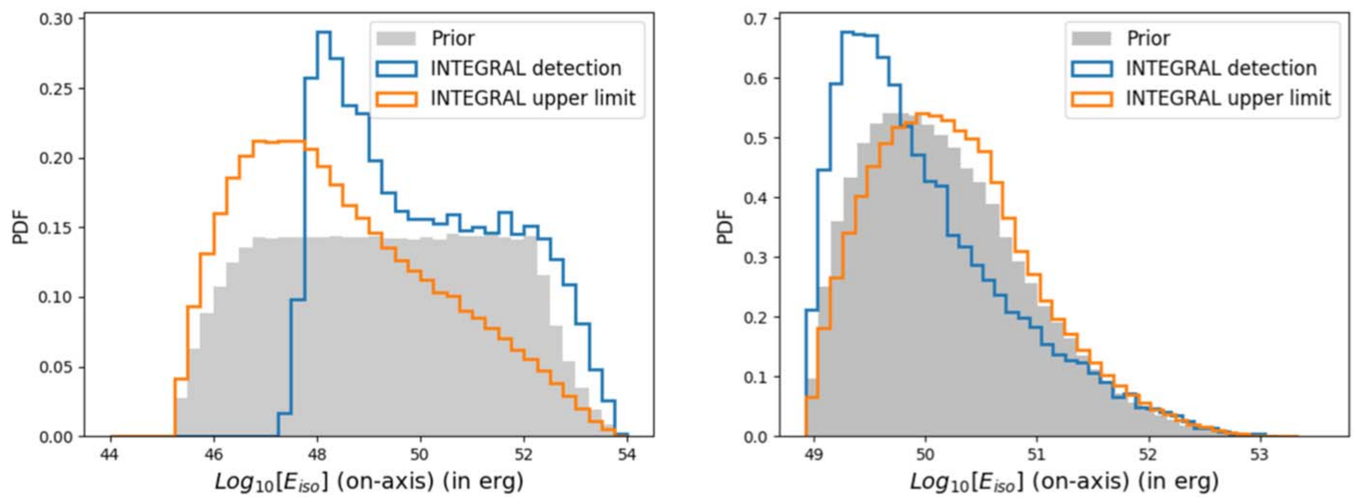

Figure 3. Constraints on the isotropic on-axis energy of the short GRB associated with S190425z assuming a Gaussian structured jet. On the left panel, the gray shades indicate the prior distribution that results from assuming uniform priors on $\log_{10}(E_{\mathrm{tot},\gamma}/\mathrm{erg})$ in the range of [44–51] and on θ_c in [3, 20] degrees. On the right panel, the same prior is used for θ_c while for $E_{\mathrm{tot},\gamma}$, a broken power-law function is used, which reproduces the observed fluence distribution of short GRBs (see text for details). The orange curve results from considering a fluence upper limit of 2×10^{-7} erg cm^{-2}, while the blue curve considers a detection of 1.6 ± 0.4 erg cm^{-2} as reported in Minaev et al. (2019). Treating the low S/N excess as a detection, the isotropic equivalent energy of an associated GRB, if viewed on-axis, is tightly constrained for a flat prior. In both cases, on-axis energy of a possible associated GRB is within the range of that of the cosmological short GRB population.

observed for typical cosmological short GRBs (Zhang et al. 2009; D'Avanzo et al. 2014), and also extend the prior to much lower values if an intrinsically low-energy burst is to arise from the merger. We used a wide uniform prior for the bulk Lorentz factor at the jet axis $5 < \Gamma_0 < 500$. This was done particularly because constraints on the initial bulk Lorentz factor from GRB 170817A is very weak (Resmi et al. 2018; Troja et al. 2018), and we do not have good prior information on the kind of outflows arising from BNS mergers.

In the next step, we chose priors that best reproduce the observed short GRB fluence distribution from Fermi 4 yr catalog (Gruber et al. 2014). We found that a broken power-law prior distribution of $E_{\mathrm{tot},\gamma}$ along with uniform distributions $3^\circ < \theta_c < 20^\circ$ and $100 < \Gamma < 500$ are able to reproduce the observed fluence distribution above 2×10^{-7} erg cm^{-2} relatively well (Mohan et al. 2019). We assumed $E_{\mathrm{tot},\gamma}$ to extend from 5×10^{47} erg to 10^{50} erg with a power-law index of -0.53 and from 10^{50} erg to 5×10^{51} erg with an index of -3.5. For the indices, we adopted values from the luminosity function used by Ghirlanda et al. (2016).

We used both these distributions along with the *INTEGRAL* observations to see constraints on a possible GRB associated with the merger. The $D_L - \iota$ distribution computed in the previous section is substituted as the prior for D_L and θ_v. We extracted marginalized posterior distributions for θ_c, Γ_0, θ_v, and $E_{\mathrm{tot,\ gamma}}$, which later we converted to the posterior of $E_{\mathrm{iso}}(0)$.

We find that the *INTEGRAL* fluence provides a good constraint to the energy of the GRB. The isotropic equivalent energies of cosmological short GRBs detected by *Fermi* GBM and *SWIFT* Burst Alert Telescope range from 10^{48}–10^{53} erg (Zhang et al. 2009). Our analysis shows that, had the observer been along the axis of the jet, a typical short GRB could have been detected along with S190425z (see Figure 3). The uniform energy prior, which has a wide range, get well constrained by the *INTEGRAL* observations. When considered as a detection, $E_{\mathrm{iso}}(0)$ is tightly constrained to be between $(4.74 \times 10^{47}$–$2.21 \times 10^{51})$ erg (blue curve in the left panel of Figure 3). On the other hand, when considered as an upper limit, the posterior (orange curve) indicates that $E_{\mathrm{iso}}(0) \leqslant 3 \times 10^{48}$ erg at 1σ level, which is broadly in agreement with the range observed for standard cosmological short GRBs. The lower end of the posterior in this case is not constrained (as expected in the absence of a detection) and hence simply follows the prior on $E_{\mathrm{iso}}(0)$ (see Figure 3, shaded gray).

On the other hand, for the second case, where we use a narrower prior distribution in energy, the observations are not able to place tight constraints on the assumed prior distribution. The 1σ posterior bounds is $1.9 \times 10^{49} < E_{\mathrm{iso}}(0) < 6.6 \times 10^{50}$. Though the posterior bounds are sensitive to the assumed prior, both prior distributions we considered here imply that the observations cannot rule out an event with typical short GRB energetics. We recall that our conclusion is sensitive to deeper limits from *INTEGRAL* as well as the refined GW posteriors on $D_L - \iota$.

The γ-ray observations cannot provide any useful constraints to the jet core angle or its initial bulk Lorentz factor. Taken either as an upper limit or as a detection, the *INTEGRAL* fluence is consistent with the expected emission from a relativistic jet. We also ran the simulations where $E_{\mathrm{iso}}(\theta_v)$ is calculated by assuming that the γ-ray emission stops below a bulk Lorentz factor of 15. The posterior distribution from such a model did not show much difference from a model where the entire jet surface is integrated to obtain E_{iso}.

4. Discussion and Conclusions

One of the important open questions from the observations of the first BNS merger GW170817 was whether the gamma-ray emission from GRB 170817A is powered by a relativistic jet, and whether this burst is one among the population of cosmological short GRBs. The absence of a strong GRB associated with S190425z, the second BNS merger candidate by LIGO/VIRGO, increased the importance of this question.

While the evolution of the broadband afterglow and proper motion of the radio afterglow of GRB 170817A confirm the presence of a relativistic jet, the low energetic γ-ray signal could still be argued to be different from cosmological short GRBs. If so, a novel class of low luminosity gamma-ray transients will be seen associated with BNS mergers. Therefore, it is important to understand whether jets are associated with BNS mergers, and if so, to obtain reliable constraints on their energetics.

In this analysis, we have shown that electromagnetic observations of S190425z are consistent with the launch of a relativistic jet typical to that of short duration GRBs. We see that a structured jet with Gaussian profile at the distance of S190425z is well consistent with the *INTEGRAL* sensitivity limits. The inferred posterior of the isotropic equivalent energy for an on-axis observer is in agreement with that of typical short GRBs. Even when we take the conservative view that *INTEGRAL* observations yielded only an upper limit, thereby allowing even low-energy explosions to remain consistent, the 1σ posterior results in $E_{\rm iso}(0) \leqslant 3 \times 10^{48}$ erg for a wide uniform prior in $E_{{\rm tot},\gamma}$. Constraints are not very tight if a broken power-law prior distribution, which reproduces the fluence distribution of standard short GRBs, is assumed for $E_{{\rm tot},\gamma}$. Nevertheless, this indicates that one need not invoke an intrinsically low-energy GRB or shock breakout to explain the absence of a strong γ-ray signal above *INTEGRAL* limits. We do not find any significant change in the results if γ-ray emission is assumed to happen only from those regions of the jet above a moderate threshold Lorentz factor.

A limitation of this approach to estimate off-axis fluence is that it cannot accommodate energy dissipation and γ-ray production mechanisms. This approach is also not sensitive to temporal and spectral evolution of the radiation, instead it returns the total fluence observed. Our conclusions are sensitive to future deeper upper limits from *INTEGRAL*. Future multi-messenger observations of BNS mergers in AdvLIGO/VIRGO 3rd observing run will certainly provide further valuable insights into the physics of these mergers and GRBs.

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