Photometric studies on the host galaxies of gamma-ray bursts using 3.6m Devasthal Optical Telescope

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Abstract.
In this article, we present multi-band photometric observations and analysis of the host galaxies for a sample of five interesting gamma-ray bursts (GRBs) observed using the 3.6m Devasthal Optical Telescope (DOT) and the back-end instruments. The host galaxy observations of GRBs provide unique opportunities to estimate the stellar mass, ages, star-formation rates, and other vital properties of the burst environments and hence progenitors. We performed a detailed spectral energy distribution (SED) modeling of the five host galaxies using an advanced tool called Prospector, a stellar population synthesis model. Furthermore, we compared the results with a larger sample of well-studied host galaxies of GRBs, supernovae, and normal star-forming galaxies. Our SED modeling suggests that GRB 130603B, GRB 140102A, GRB 190829A, and GRB 200826A have massive host galaxies with high star formation rates (SFRs). On the other hand, a supernovae-connected GRB 030329 has a rare low-mass galaxy with a low star formation rate. We also find that GRB 190829A has the highest (in our sample) amount of visual dust extinction and gas in its local environment of the host, suggesting that the observed very high energy emission from this burst might have a unique local environment. Broadly, the five GRBs in our sample satisfy the typical correlations between host galaxies parameters and these physical parameters are more common to normal star-forming galaxies at the high-redshift Universe. Our results also demonstrate the capabilities of 3.6m DOT and the back-end instruments for the deeper photometric studies of the host galaxies of energetic transients such as GRBs, supernovae, and other transients in the long run.

Keywords. gamma-ray burst: general, galaxies: dwarf, methods: data analysis, techniques: photometric.

1. Introduction
Gamma-ray bursts (GRBs) are the most luminous and fascinating sources observed in the Universe since the Big bang. Their unique characteristic properties provide an excellent opportunity to study compact binaries, the evolution of massive stars, and extreme physical phenomenon out to very large distances (Kumar & Zhang, 2015). GRBs are supposed to be originated from relativistic jets launched either due to the merger of two compact objects producing short GRBs ($T_{90} \leq 2$ sec) or due to the birth of a stellar-mass black hole or a rapidly rotating magnetized neutron star during the core-collapse of massive stars giving rise to long GRBs ($T_{90} > 2$ sec). However, the origin of a few short bursts (e.g., GRB 090426 and GRB 200826A) from the collapse of massive stars and the origin of a few long bursts (e.g., GRB 060614 and GRB 211211A) from the binary merger challenges our current understanding of the nature of possible progenitors of GRBs. These examples suggest that at least some of the short GRBs might be originated from collapsars (Antonelli et al., 2009; Ahumada et al., 2021; Zhang et al., 2021) and some of the long GRBs might be originated from mergers (Della Valle et al., 2006; Troja et al., 2022). Followed by the prompt emission and longer-lasting multi-wavelength afterglow phases (Piran, 2004; MAGIC Collaboration et al., 2019), late-time observations of the host galaxies
are of crucial importance to examine the burst environment and, in turn, about the possible progenitors.

GRBs can be used to study the galaxies both at high (the most distant, GRB 090423 with spectroscopic $z \sim 8.2$) and low (nearest, GRB 170817A $z \sim 0.0097$) redshifts due to their intrinsic brightness (much higher signal to noise ratio; Basa et al. 2012). The GRB host galaxy characteristics of long and short GRBs are largely different such as morphology, stellar population, offsets, etc. but share common properties too for a fraction of observed populations. These observed characteristics are likely associated with the physical conditions surrounding possible progenitors producing GRBs. Long GRBs are generally localized in active star-forming and young stellar population dwarf galaxies. Since long GRBs are likely to be related to the death of massive stars, they are widely cited as robust and potentially unbiased tracers of the star formation and metallicity history of the Universe up to $z \sim$ eight (Savaglio et al., 2009). Host galaxy observations of long GRBs suggest that they preferentially occur in low-metallicity galaxies (Mannucci et al., 2011). On the other hand, short GRBs are expected in any type of galaxy associated with an old stellar population (Berger, 2009). Their locations relative to their host centers have a median physical offset of about five kpc, which is about four times larger than the median offset for long bursts (Fong & Berger, 2013). Therefore, host parameters can constrain the nature of GRBs’ possible progenitors and environments.

In the pre-Swift era (before 2004), there were few bursts with measured redshifts. In this era, the host galaxies were intensely studied once the redshift was known to be low ($z \leq 0.3$). In Swift era, the number of GRBs with measured redshift values increases but still $\sim 25\%$ of the localized ones and could still be biased against dusty events. Savaglio et al. (2009) studied the host galaxy properties for a large sample of GRBs hosts and suggested that GRB hosts are similar to normal star-forming galaxies in both the nearby and the distant universe. Perley et al. (2016a,b) examined an unbiased sample of the host galaxies of long GRBs (mainly photometric) and proposed that the dusty bursts are generally found in massive host galaxies. It gives a clue that the massive galaxies (star-forming) are typical and homogeneously dusty at higher redshift. On the other hand, low-mass galaxies (star-forming) have a small amount of dust in their interstellar medium (to some level). Also, Svensson et al. (2010); Japelj et al. (2018) presented comparative studies of the host galaxies of GRBs and compared their properties with those of core-collapse supernovae (CCSNe). More recently, Taggart & Perley (2021) presented a comprehensive study of a large sample of core-collapse supernova (CCSN) host galaxies and compared with the host galaxies of the nearest long GRBs and superluminous supernova (SLSN) and found a hint that host-galaxy mass or specific star-formation rate is more fundamental in driving the preference for SLSNe and long GRBs in unusual galaxy environments.

Deeper optical photometric follow-up observations of energetic transients such as afterglows of long and short GRBs are frequently carried out (Kumar et al., 2021a; Dimple et al., 2020; Gupta et al., 2021c,d,e, 2022; Kumar et al., 2022) using the recently commissioned largest Indian optical telescope, i.e., 3.6m DOT situated at Devasthal observatory of Aryabhatta Research Institute of Observational Sciences (ARIES) Nainital and the back-end instruments (Pandey et al., 2018; Ojha et al., 2018; Kumar et al., 2021b). Observations of galaxies and other objects of low surface brightness are also carried out using the 3.6m DOT (Kumar et al., 2021b; Panwar et al., 2021). In this work, we performed the spectral energy distribution modeling of a sample of five host galaxies of GRBs observed by the 3.6m DOT/back-ends and compared the results with other well-studied samples of host galaxies. We observed the host galaxies of these five bursts subject to the availability of the observing time of the CCD IMAGER and clear sky conditions (see section 2.). This work demonstrates the capabilities of deep follow-up observations of such faint and distant hosts of explosive transients using the 3.6m DOT. We have arranged this article in the following sections. In section 2., we present our host galaxies sample (with brief details about each burst) and their multi-band photometric observations taken with 3.6m DOT. In section 3., we present the host galaxy spectral energy distribution modeling of our photometric data along those obtained from literature using Prospectors (version 1.1.0). In section 4., we have given the SED modeling results and comparison with other known host galaxies. Finally, in section 5., we have presented the summary and conclusion of the present work. Throughout this paper, we consider following cosmological values: the Hubble parameter $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, density parameters $\Omega_m = 0.73$, and $\Omega_k = 0.27$.

### 2. Sample of Host galaxies, observations with the 3.6m DOT

In this section, we provide details of multi-band photometric observations of the host galaxies of the sam-
2.1 GRB 030329 (associated SN 2003dh):

GRB 030329 was triggered by many detectors on-board the High Energy Transient Explorer (HETE-2) mission at 11:37:14.67 UT on 2003 March 29. The prompt emission light curve of this GRB consists of two merging emission pulses with a total duration of ∼25 s in 30-400 keV energy band. Later on, a multi-wavelength follow-up observations campaign of GRB 030329 revealed the discovery of optical (Peterson & Price, 2003), X-ray (Marshall & Swank, 2003), and radio counterparts (Berger et al., 2003). Greiner et al. (2003) measured the redshift of the burst (z) = 0.1685 using the early spectroscopy observations taken with the Very Large Telescope (VLT). Furthermore, a late-time bump in the optical light curve along with spectroscopic observations confirms detection of associated broad-line type Ic supernova (Hjorth et al., 2003), establishing the relationship between the afterglow of long GRBs and supernovae. Östlin et al. (2008) utilizes the spectral evolutionary models to constrain the progenitor and suggested collapsar scenario for the progenitor of GRB 030329/SN 2003dh.

We performed the host galaxy observations of GRB 030329 using 4K × 4K Imager mounted on the axial port 3.6m DOT in March 2017. Multiple frames with an exposure time of 600 s were taken in R and V filters. The host galaxy of GRB 030329/SN 2003dh is clearly detected in both filters. A finding chart taken in the R filter is shown in the upper-left panel of Fig. 2.

2.2 Short GRB 130603B (associated kilonova emission):

This burst was detected by Burst Alert Telescope (BAT) on-board Swift mission at 15:49:14 UT on 03<sup>rd</sup> June 2013 at the position RA = 172.209, DEC = +17.045 degree (2000) with an uncertainty of three arcmin. The prompt emission BAT light curve consists of the fast-rising and exponential decay (FRED) like single structure with T<sub>90</sub> duration of 0.18 ± 0.02 s (in 15-350 keV), classifying this burst as a short-duration GRB (Barthelmy et al., 2013). Thöne et al. (2013) obtained the afterglow spectrum using 10.4m GTC and reported the redshift of the burst z = 0.356. Later on, the late time near-infrared (NIR) observations reveal the detection of the kilonova emission (the first known case) accompanying with short GRB 130603B, supporting the merger origin of short GRBs (Tanvir et al., 2013). de Ugarte Postigo et al. (2014) studied the environment and proposed that the explosion site of this burst is not similar to those seen in the case of long GRBs.

We observed the host galaxy of short GRB 130603B using 3.6m DOT in B and R filters with an exposure time of 2x300 s in each on 23<sup>rd</sup> March 2017.
We detected a bright galaxy (see the upper-right panel of Fig. 2) in both the filters.

2.3 **GRB 140102A (early reverse shock emission):**

GRB 140102A was jointly detected by Fermi (by both Gamma-ray Burst Monitor (GBM) and Large Area Telescope (LAT)) and Swift BAT detectors. We carried out an early follow-up of the optical afterglow of GRB 140102A reveals the rarely observed reverse shock signature in the light curve. We also constrain the redshift of the burst $z = 2.02$ using joint X-ray and optical SED. We calculated the magnetization parameter using the afterglow modeling of GRB 140102A and suggested that the jet composition could be dominant with a moderately magnetized outflow, in this case, (Gupta et al., 2021a). Furthermore, we carried out the host galaxy observations of GRB 140102A in the R filter (with a total exposure time of 45 minutes) using 3.6m DOT on 16 January 2021. However, we could not detect the host galaxy (see the lower-left panel of Fig. 2), but we could constrain the deep limiting magnitude.

2.4 **GRB 190829A (nearest Very high energy (VHE) burst):**

GRB 190829A was detected by Fermi GBM (at 19:55:53 UT), and Swift BAT (at 19:56:44.60 UT) on 29$^{th}$ August 2019. de Naurois (2019) reported the detection of very high energy (VHE) emission from the source using H.E.S.S. observations. We studied the prompt emission characteristics of the two-episodic low-luminous GRB 190829A, and found that the first episode is an Amati outlier, showing the peculiar nature of the prompt emission (Chand et al., 2020; Gupta et al., 2021b). Furthermore, we calculated the redshift of the burst $z = 0.0785$ using 10.4m GTC spectroscopic observations, making the event the nearest VHE detected GRB along with the detection of associated supernova (Hu et al., 2021). However, it is still an unsolved question that VHE emission is originated due to their environment or its emission mechanism (de Ugarte Postigo et al., 2020).

The associated host galaxy of GRB 190829A is a significantly bright SDSS galaxy (SDSS J025810.28-085719.2). We observed this galaxy using 3.6m DOT in B, R, and I filters on 03$^{rd}$ October 2020. The host galaxy is clearly detected in each filter of our observations. A finding chart for the host galaxy of GRB 190829A is shown in the lower-right panel of Fig. 2.

2.5 **GRB 200826A (shortest long burst):**

GRB 200826A was detected by Fermi GBM at 04:29:52.57 UT on 26 August 2020 with a $T_{90}$ duration of 1.14 s in the GBM 50-300 keV energy range (Mangan et al., 2020). Late-time optical follow-up observations revealed the bump in the light curve, consistent with the supernova emission. Although the prompt properties of the burst are typical to those of short GRB, late-time follow-up observations confirm a collapsar origin (Ahumada et al., 2021). Ahumada et al. (2021) suggested that the burst is the shortest long burst with SN bump and lie on the brink between a successful and a failed collapsar.

We have obtained the optical and NIR photometric data of the host galaxy of GRB 200826A using the TIFR-ARIES Near-Infrared Spectrometer (TANSPEC; Ojha et al., 2018) mounted on the 3.6m DOT, Nainital, India during the nights of 2020 November. TANSPEC is a unique instrument that provides simultaneous wavelength coverage from 0.5-2.5 μm in imaging and spectroscopic modes. We have given exposures of one hour, 35 minutes, 35 minutes in I (4$^{th}$ November 2020), J (4$^{th}$ November 2020), K (11$^{th}$ November 2020) bands, respectively. In I band, 12 frames of 5 min exposure, whereas, in J and K bands, three sets of 20 × 5 sec exposure at seven dithered positions (total of 35 minutes in J and K bands) were taken with TANSPEC. We have used standard data reduction procedures for the image cleaning, photometry, and astrometry (for details, see Sharma et al., 2020). The host galaxy is detected in the I band as 22.71 ± 0.10 mag, and there was an upper limit of J > 20.56 mag and K > 19.55 mag. A finding chart of the host galaxy of GRB 200826A taken with TANSPEC is shown in Fig. 3.

3. **Panchromatic SED modeling**

In our previous studies (Pandey et al., 2019; Gupta et al., 2021a), LePHARE software is used for the modeling of the host galaxies, and it suffers from a major limitation, i.e., using only chi-square statistics to the best fit solution. The results of LePHARE software are primarily affected by degeneracy among parameters as it could not provide the posterior distributions. Therefore, in this work, we utilized an advanced software called Prospector (version 1.1.0) for SED fitting to constrain the host galaxies properties of our sample of five hosts. Prospector (Leja et al., 2017; Johnson et al., 2021) software (stellar population modeling code) for modeling the SEDs using the measured photometric magnitudes values of the host galaxies. Prospector utilizes a library of Flexible Stellar Population Synthesis models (Conroy et al., 2009). It is advanced software that determines the best-fit solution to the SED model fitting using Dynesty (implements dynamic nested sampling algorithm) and produces the
Figure 2. The R-band finding charts of the host galaxies of GRB 030329 (top left), GRB 130603B (top right), GRB 140102A (bottom left), and GRB 190829A (bottom right) were obtained using 4K×4K CCD Imager mounted on the 3.6m DOT (Pandey et al., 2018; Kumar et al., 2021b). The position of the host galaxies in the frames is marked with circles.

posterior distributions for the model parameters. The posterior distributions are useful to verify the degeneracy between the model parameters. We performed the SED fitting to photometric data for each of the host galaxies of our sample at their respective fixed redshift values. We have used the parametric_sfh model to calculate the stellar population properties such as stellar mass formed (\( M_\ast \), in units of solar mass), stellar metallicity (\( \log \frac{Z}{Z_\odot} \)), age of the galaxy (\( t \)), rest-frame dust attenuation for a foreground screen in mags (\( A_V \)), and star formation timescale (\( \tau \)) for an exponentially declining star formation history (SFH). We have set these host galaxy model parameters free to determine the posterior distribution and consider uniform priors across the allowed parameter space within Flexible Stellar Population Synthesis models. We have fixed the maximum values of the prior of the age of the galaxies corresponding to the age of the Universe at their respective measured redshifts values. For the host SED modeling using stellar population models, we consider Milky Way extinction law (Cardelli et al., 1989) and Chabrier initial mass function (Chabrier, 2003). We calculated the

\[ \text{https://github.com/bd-j/prospector} \]
star formation rate using the following equation taken from Nugent et al. (2020):

$$\text{SFR}(t) = M \times \left[ \int_0^t e^{-t/\tau} dt \right]^{-1} \times te^{-t/\tau}$$  \hspace{1cm} (1)$$

4. Results

4.1 SED modeling

This section presents the results of the host galaxies modeling of our sample. We corrected the values of the observed magnitudes (AB system) for the foreground galactic extinction for each galaxy following Schlafly & Finkbeiner (2011) and used them as input to Prospector for the SED modeling of galaxies. The best-fit SEDs are shown in Fig. 4 (corner plots are shown in Fig. 8 of the appendix), and their results thus obtained are tabulated in Table 1.

4.1.1 GRB 030329: We modeled the SED (constructed using the data taken using 3.6m DOT along with those published in Gorosabel et al. (2005)) of the host galaxy of GRB 030329 (a low redshift galaxy) using Prospector. The best fit SED using nested sampling via dynesty method provide the following physical parameters: stellar mass formed (log(M/M_⊙)) = 7.98 ± 0.12, stellar metallicity (log(Z/Z_⊙)) = -0.29 ± 0.18, age of the galaxy (t_{gal}) = 1.21^{+0.59}_{-0.44} Gyr, rest-frame dust attenuation (A_V) = 0.12^{+0.15}_{-0.08} mag, and log(τ) = 2.11^{+1.23}_{-1.19}. Furthermore, we derive the star formation rate of the galaxy = 1.57 ×10^{-1} M_⊙ yr^{-1} and it is consistent with the value report by Hjorth et al. (2003) based on the host galaxy emission line properties. Our analysis suggests for a low mass, and low star formation galaxy for GRB 030329 (Gorosabel et al., 2005).

4.1.2 GRB 130603B: We performed the modeling of the photometric data of the host galaxy obtained using 3.6m DOT along with those taken with other facilities (OSN, CAHA, and GTC) using the LePHARE software and presented the results in (Pandey et al., 2019). We find that the burst’s environment is undergoing moderate star formation activity (Pandey et al., 2019). However, we noted that LePHARE software have some major limitations for such analysis, which we discussed in section 3. Therefore, in this work, we performed the SED modeling of GRB 130603B using an advanced software called Prospector, and we derive following host parameters: log(M/M_⊙) = 10.63^{+0.09}_{-0.10}, log(Z/Z_⊙) = -1.50^{+0.36}_{-0.25}, age of the galaxy = 7.09^{+1.76}_{-2.14} Gyr, A_V = 1.65^{+0.29}_{-0.23} mag, and log(τ) = 1.78^{+0.76}_{-0.72}. We calculated the star formation rate of the galaxy = 11.57 M_⊙ yr^{-1}. Our results suggest that the host galaxy of GRB 130603B has a high mass galaxy with a moderate star formation activity, consistent with those reported in Pandey et al. (2019).

4.1.3 GRB 140102A: In our recent work (Gupta et al., 2021a), we performed the SED modeling of the host galaxy of GRB 140102A using LePHARE software (uses χ^2 statistics) with PEGASE2 stellar synthesis population models library. We obtained the best fit solution with the following host galaxy parameters: age of the stellar population in the host galaxy = 9.1 ± 0.1 Gyr, mass = (1.9 ± 0.2) × 10^{11} M_⊙, and SFR = 20 ± 10 M_⊙ yr^{-1} with a relatively poor chi-square value (χ^2 = 0.1). This indicates that the error bars are overestimated or the model is too flexible that may cause a large degeneracy in model parameters. For the present work, we collected the photometric observations for the host galaxy of GRB 140102A from our recent work Gupta et al. (2021a), and performed the modeling using Prospector due to the limitation of LePHARE software as mentioned above. We have frozen the redshift z = 2.02 obtained from afterglow SED of GRB 140102A, to model the host SED using Prospector. We find stellar mass of log(M/M_⊙) = 11.88^{+0.34}_{-0.10} M_⊙, stellar metallicity of log(Z/Z_⊙) = -0.19^{+0.78}_{-1.03} age of the galaxy (t_{gal}) = 8.51^{+3.30}_{-3.58} Gyr, dust extinction of A_V = 1.35^{+0.25}_{-0.25} mag, and with a moderate star formation rate of 52.90
Figure 4. Spectral energy distribution modeling of the host galaxies of our sample: The best fit modeled spectrum and photometry obtained using Prospector are presented in cyan, blue, green, black, magenta for GRB 030329, GRB 130603B, GRB 140102A, GRB 190829A, and GRB 200826A, respectively. The photometry data of the host galaxies (corrected for galactic extinction) in the AB system is shown with red circles.

M⊙ yr⁻¹. The results indicate that the host was a high-mass galaxy with high star-formation rate, consistent with those obtained from LePHARE.

4.1.4 GRB 190829A: GRB 190829A has a very bright and nearby SDSS host galaxy. We modeled the SED using the data observed using 3.6m DOT along with those reported in literature (see Table 2 in appendix). We find stellar mass of log(M/M⊙) = 12.04 ± 0.09, stellar metallicity of log(Z/Z⊙) = -2.39 ± 0.24, age of the galaxy (t_gal) = 9.91 ± 1.85 Gyr, dust extinction
of $A_V = 2.37^{+0.22}_{-0.20}$ mag, and with a moderate star formation rate of 6.87 $M_\odot$ yr$^{-1}$. The SED modeling indicates that the host of GRB 190829A is a massive galaxy with a very high star-formation rate.

### 4.1.5 GRB 200826A: We modeled the host galaxy of GRB 200826A (Rossi et al., 2022) using the observed magnitude values using TANSPEC mounted on the main axis of 3.6m DOT along with data published in Ahumada et al. (2021), and find stellar mass of log(M/M_\odot) = 9.92^{+0.08}_{-0.10}, stellar metallicity of log(Z/Z_\odot) = -0.37^{+0.21}_{-0.21}, age of the galaxy ($t_{gal}$) = 4.74^{+1.53}_{-1.90} Gyr, dust extinction of $A_V = 0.19^{+0.17}_{-0.11}$ mag, and with a moderate star formation rate of $3.49 M_\odot$ yr$^{-1}$. These parameters are typical to those observed for long GRBs host galaxies and consistent with Ahumada et al. (2021).

### 4.2 Comparison with known sample of host galaxies

We compared the host galaxy’s properties of our sample (see Table 1) with other well-studied samples of GRB host galaxies from the literature (Savaglio et al., 2006, 2009) and GALEX-SDSS-WISE Legacy Catalog (GSWLC; Salim et al. 2016, 2018). The physical parameters (stellar mass and star formation rate) distribution for the host galaxies of GRBs and GSWLC are shown in Fig. 5 (upper left and right panels). The positions of the host galaxies presented in our sample are shown with downwards arrows. We noticed that the average value of the stellar mass of the galaxies in the GSWLC is higher than the average values of the stellar mass of the host galaxies of long and short GRBs. On the other hand, the average value of star formation rate (SFR) of the galaxies in the GSWLC is lower than the average values of the stellar mass of the host galaxies of long and short GRBs. Furthermore, we studied possible correlations of the stellar mass of the host galaxies versus SFR and the stellar mass of the host galaxies versus specific star formation rates (SSFRs). For normal star-forming galaxies, the correlation between the stellar mass and SFR is defined as the “main sequence.” This correlation reveals the possible procedures of the star formation histories of galaxies. If the correlation is tighter, it suggests that the star formation history traces stellar mass growth more smoothly. On the other hand, if the correlation is weaker (high scatter), it suggests a random star formation history (Daddi et al., 2007; Noeske et al., 2007; Finlator et al., 2011).

Hence, GRB host galaxy properties can be characterized by comparing them with the main sequence. The relation between the stellar mass of the host galaxies as a function of SFRs for GRBs and GSWLC is shown in Fig. 5 (bottom left panel). The position of the host galaxies presented in our sample is shown with colored squares. The colored solid lines and shaded regions in both the correlations indicate the best fit power-law functions and their dispersion calculated for normal star-forming galaxies from NEOWIRM Medium-Band Survey (NMBS) sample at redshift values of 0.67 (the mean redshift of the sample), 1 and 2 (the mean redshift of long GRBs), respectively (Whitaker et al., 2012). We noticed that the host galaxies’ physical properties of GRBs are more common to normal star-forming galaxies at the high-redshift Universe in comparison to the low-redshift Universe (Perley et al., 2013; Hashimoto et al., 2019).

In addition, we found that GRBs in our sample follow Mass-SFR correlation (see Fig. 5) as described previously by Savaglio et al. (2006, 2009). Furthermore, we notice that the star formation rate of GRB 130603B, GRB 140102A, GRB 190829A, and GRB 200826A in our sample are higher in comparison to the median value of $2.5 M_\odot$ yr$^{-1}$ (Savaglio et al., 2009). On the other hand, GRB 030329 has a low star formation rate. The host galaxies of GRB 130603B, GRB 140102A, GRB 190829A, and GRB 200826A have higher mass than the galaxies with semi-star formation rates. We also compared the SSFRs of the host galaxies of our sample with the GRB’s host galaxies sample studied by Savaglio et al. (2006, 2009) and normal star-forming galaxies (GSWLC; Salim et al. 2016, 2018). The SSFR indicates the intensity of star formation in particular galaxies. The correlation between the stellar mass of the galaxies and SSFRs suggests how the galaxies compose their stellar populations (Lehnert et al., 2015). We noticed that other than GRB 030329, all other four host galaxies have lower SSFR in comparison to the average value of 0.8 Gyr$^{-1}$ (see Fig. 5), suggesting a lower intensity of star-formation for these host galaxies. On the other hand, the observed higher value specific star formation rate for the host galaxy of GRB 030329 indicates a young, starbursting galaxy (Castro Cerón et al., 2006). The relation between SSFR-Mass also indicates that physical properties of the host galaxies of GRBs are more common to normal star-forming galaxies at the high-redshift Universe (Perley et al., 2013; Hashimoto et al., 2019).

### 4.2.1 Host galaxies of GRBs, and Supernovae: Long GRBs usually occur at high redshift; however, some of the nearby long bursts are associated with broad-line type Ic supernovae (stripped-envelope). However, it is still not understood that all long GRBs are connected with broad-line type Ic supernovae, and we could only detect the near ones due to the observa-$^5$This catalog comprises the properties of ~ 700,000 galaxies with measured redshifts values below 0.3 using SDSS.
Figure 5. Top left panel: The distribution of stellar mass for the host galaxies of GRBs and galaxies studied in GALEX-SDSS-WISE Legacy Catalog (right side Y-scale). Top right panel: The distribution of SFR for the host galaxies of GRBs and galaxies studied in the GALEX-SDSS-WISE Legacy Catalog (right side Y-scale). The positions of the host galaxies presented in our sample are shown with downwards arrows. Bottom left panel: The stellar mass of the host galaxies versus star formation rate for our sample, obtained from the host SED modeling. Square markers indicate the host galaxies’ position for our sample. The dashed line indicates a constant specific star formation rate of 1 Gyr$^{-1}$. Bottom right panel: The stellar mass of the host galaxies versus specific star formation rate for our sample. Square markers indicate the host position for our sample. The dashed lines indicate the constant star formation rates of 0.1, 1, 10, and 100 M yr$^{-1}$ from left to right. Black and red circles show the long GRBs and short GRBs host galaxies with star formation rates (bottom left) and specific star formation rates (bottom right) calculated from GHostS during 1997 to 2014 (Savaglio et al., 2006, 2009). The grey dots show the location of GSWLC galaxies in both the correlations Salim et al. 2016, 2018. The colored solid lines and shaded regions in both the correlations indicate the best fit power-law functions and their dispersion calculated for normal star-forming galaxies from NEWFIRM Medium-Band Survey (NMBS) sample at redshift values of 0.67 (the mean redshift of the sample), 1 and 2 (the mean redshift of long GRBs), respectively (Whitaker et al., 2012).
Figure 6. The stellar mass of the host galaxies versus star formation rate for GRBs connected with supernovae in our sample, obtained from the host SED modeling. Circles, stars, and squares markers indicate the position of host galaxies of CCSN, superluminous supernovae, and long GRBs connected with supernovae, respectively, taken from Taggart & Perley (2021). The right side Y-scale shows the corresponding $A_V$ values.

novae and with supernovae are not much different. Out of four long GRBs in our sample, three GRBs (GRB 030329/SN 2003dh, GRB 190829A/ SN 2019oyw, and GRB 200826A) were associated with broad-line type Ic supernovae. We compared (mass as a function of SFR) the results of these GRBs/SNe with those published in Taggart & Perley (2021). We find that GRB 030329 and GRB 200826A follow the correlation plane of long GRBs and CCSN; however, the host galaxy of GRB 190829A lies on the right side of the distribution (see Fig. 6). We searched the host galaxy (SDSS) of GRB 190829A in GSWLC sample studied by Salim et al. (2016, 2018) and found that the SFR and Stellar-mass values of the host galaxy (ObjID: 1237652899156721762) of GRB 190829A are log (SFR)$ = 0.395 \pm 0.103 \, M_\odot \, yr^{-1}$, log(M/M$_\odot = 11.256 \pm 0.012$, respectively. These values also indicate that the host galaxy of GRB 190829A is a massive and high star-forming galaxy, consistent with our results.

4.3 Dust and gas in the host galaxies:

We calculated the dust extinction in the local environment of the host galaxies of our sample and compared

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$^6$The model fit used by Salim et al. (2016, 2018) is underfitting the observed data (reduced chi-square = 2.15)
them with a larger sample of host galaxy of GRBs (Kann et al., 2006, 2010; Krühler et al., 2011) / GSWLC (Salim et al., 2016, 2018) galaxies taken from the literature. We determine the visual dust extinction in rest-frame (A_v) using the host galaxy SED modeling of each burst in our sample (see section 3, for more details). Fig. 7 (top panel) shows the distribution of visual extinction (in the source frame) of the host galaxies in our sample. For the comparison, we have also shown the distribution of visual extinction for GRBs in pre-Swift (Kann et al., 2006), post-Swift (Kann et al., 2010) era, dusty GRBs (Krühler et al., 2011) and GSWLC (Salim et al., 2016, 2018). We find that A_v values are distributed over a wide range for our sample, and part of host galaxies (GRB 130603B, GRB 140102A, and GRB 190829A) are extinguished by dust. Moreover, these galaxies (dusty) typically have higher stellar mass, consistent with previous studies (Perley et al., 2009; Krühler et al., 2011). In addition, we also noted that the A_v values ≤ 1 for other than the dusty sample, suggesting that the dusty galaxies (~ 20 %) are highly extinguished and might cause optical darkness (Jakobsson et al., 2004; Greiner et al., 2011; Gupta et al., 2021c).

Fig. 7 (middle panel) shows the evolution of host visual extinction as a function of redshift for our sample along with those data points published by (Kann et al., 2006, 2010; Krühler et al., 2011; Schady et al., 2012). We noticed that the visual extinction is decreasing with redshift, although it might be due to the selection effect as there are only a few GRBs with redshift ≥ 5, and the observation of dusty galaxies at such high redshift is very difficult (Kann et al., 2010).

Furthermore, we used the spectral analysis results of the X-ray afterglow data from the literature to constrain the intrinsic hydrogen column density (N_H (z)) of each burst in our sample. The X-ray afterglow spectra of GRBs could be typically described using a simple absorption power-law model consists of three components: a Galactic absorption (N_H), host absorption (N_H (z)), and a power-law component due to synchrotron emission. We obtained N_H (z) values of GRB 030329 from Tiengo et al. (2004), GRB 130603B from Swift X-ray telescope web-page maintained by Phil Evans, GRB 140102A from Gupta et al. (2021a), GRB 190829A from Chand et al. (2020), and for GRB 200826A from Ahumada et al. (2021), respectively. The distribution of host dust extinction and gas column densities in the local environment for our sample, along with other data points taken from the literature, are shown in Fig. 7 (bottom panel). We noticed that GRB 190829A has a considerable amount of dust and gas in the local environment of its host galaxy. The observed considerable amount of dust and gas might be related to the associated VHE emission from GRB 190829A, a similar dusty environment is also seen in the case of other VHE detected bursts such as GRB 190114C (de Ugarte Postigo et al., 2020) and GRB 201216C (Rhodes et al., 2022). However, due to the limited number of VHE detected GRBs, it is still an unsolved problem whether VHE detected GRBs require unique environments to emit the VHE emission or VHE emission is only due to the burst emission mechanisms such as Synchrotron Self Compton (MAGIC Collaboration et al., 2019; Abdalla et al., 2019; de Ugarte Postigo et al., 2020; Gupta et al., 2021b).

5. Summary and Conclusion

The observed gamma-ray prompt emission properties of GRBs do not always depict about nature of their progenitors and environments and, in turn, about an ambiguous classification. Recently, the origin of a few short bursts (e.g., GRB 090426 and GRB 200826A) from the collapse of massive stars (Antonelli et al., 2009; Ahumada et al., 2021) and long GRBs (e.g., GRB 211211A, and GRB 060614) from the merger of two compact objects (Troja et al., 2022; Rastinejad et al., 2022; Yang et al., 2015) are confirmed. These examples suggest that at least some of the short GRBs might be originated from collapsars, and some of the long GRBs might be originated from compact mergers. Therefore, the late-time observations of the host galaxies are crucial in examining the burst environment and, in turn, the possible progenitors, especially for the hybrid cases. In this paper, we present the photometric observations of the five interesting GRBs’ host galaxies observed using India’s largest optical telescope (3.6m DOT) to constrain the environment of these bursts, nature of possible progenitors, and explore the deep observations capabilities of 3.6m DOT. Our optical-NIR multi-band data of these five hosts, along with those published ones, were used to perform multi-band modeling of the host galaxies using Prospector software (version 1.1.0). We noted that the host galaxies in our sample have a wide range of physical parameters (see Table 1). The host galaxies of GRB 130603B, GRB 140102A, GRB 190829A, and GRB 200826A have a massive stellar population galaxy with a high star formation rate. However, GRB 030329 has a low-mass galaxy with a low star formation rate, such host galaxies having a low-mass with a low star formation rate are rare (Castro Cerón et al., 2010). We compared the stellar population properties (such as SFR, SSFR, Mass, etc.) of the host galaxies of our sample with a large sample of long and short bursts along with those taken from literature specifically with GSWLC. We find that all the bursts in our sample satisfy the typical known correlation between host galaxy parameters. We noted
that the GRBs generally occur in host galaxies that have less massive and high star-forming galaxies than GSWLC galaxies. Further, the host galaxies' physical properties of GRBs are more common to normal star-forming galaxies than their progenitors.

In addition, we obtained the X-ray hydrogen column densities from the X-ray afterglow observations of these bursts and studied its distribution with optical extinction. We find that GRB 190829A has a considerable amount of dust and gas in the local environment of its host galaxy. A dusty environment is also seen in the case of other VHE detected bursts such as GRB 190114C (de Ugarte Postigo et al., 2020) and GRB 201216C (Rhodes et al., 2022). It suggests that VHE detected GRBs might require a unique local environment for VHE emission to occur. Unfortunately, due to the small size of the present sample, it is difficult to quantify the selection effects, which further limits a robust statistical analysis. Our results demonstrate that the back-end instruments (such as IMAGER and TANSPEC) of 3.6m DOT have a unique capability for optical-NIR deep observations of faint objects such as host galaxies of GRBs and other interesting transients in the near future. Also, in the near future, systematic studies (with a larger sample) of the host galaxies along with prompt emission and afterglow properties of hybrid GRBs may play a crucial role in understanding their progenitors.

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Table 1. The stellar population properties of the host galaxies of our sample were obtained using spectral energy density modeling using Prospector. NH host and log(e) denote the intrinsic column density and evidence values, respectively.

| GRB   | RA (J2000) | DEC (J2000) | z    | log(M/L_⊙) | log(Z/Z_⊙) | A_v  | t_host (Gyr) | log(e) | NH_host (cm^-2) |
|-------|------------|-------------|------|------------|------------|------|--------------|--------|-----------------|
| 030329| 161.21     | 21.52       | 0.1685 | -0.29       | 2.02       | 11.54 | 1.21         | 128.95 | 2 × 10^{20}     |
| 130603B| 172.20     | 17.07       | 0.356 | 10.63       | -1.50       | 1.65  | 7.09         | 169.89 | 4.5 × 10^{21}   |
| 140102A| 211.92     | 1.33        | 2.02  | 11.54       | -0.29       | 1.23  | 2.23         | 106.06 | 6.1 × 10^{21}   |
| 190829A| 44.54      | -8.96       | 0.0785 | 12.04       | -2.39       | 2.37  | 9.91         | -447.91| 1.12 × 10^{22}  |
| 200826A| 6.78       | 34.03       | 0.748 | 9.92        | -0.37       | 0.19  | 4.74         | 118.51 | 6 × 10^{20}     |
Figure 8. The posterior distributions for the SED model parameters of GRB 030329 (cyan), GRB 130603B (blue), GRB 140102A (green), GRB 190829A (black), and GRB 200826A (magenta) obtained using nested sampling via `dynesty` using `Prospector` software.
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Table 2. Log of the host galaxy panchromatic observations of our sample taken with 3.6m DOT and those reported in the literature. The magnitude shown with star markers is in the Vega system. NOT, CAHA, GTC, and LDT denotes the Nordic Optical Telescope, Centro Astronómico Hispano-Alemán, Gran Telescopio Canarias, and Lowell Discovery Telescope, respectively.

| Date          | Exposure (s) | Magnitude (AB) | Filter | Telescope | References                  |
|---------------|--------------|----------------|--------|-----------|-----------------------------|
| **GRB 030329**|              |                |        |           |                             |
| 24.03.2004    | 5x900        | 23.45 ± 0.10   | U      | 2.56m NOT | Gorosabel et al. (2005)     |
| 24.03.2004    | 3x600        | 23.26 ± 0.07   | B      | 2.56m NOT | Gorosabel et al. (2005)     |
| 05.01.2004    | 113x60       | 22.42 ± 0.16   | J      | 3.5m CAHA | Gorosabel et al. (2005)     |
| 06.01.2004    | 109x60       | 22.55 ± 0.24   | H      | 3.5m CAHA | Gorosabel et al. (2005)     |
| 07.01.2004    | 99x60        | > 21.57        | K      | 3.5m CAHA | Gorosabel et al. (2005)     |
| **23.03.2017**| **3x600**    | **22.81 ± 0.13**| V      | 3.6m DOT  | Present work                |
| **23.03.2017**| **4x600**    | **22.83 ± 0.07**| R      | 3.6m DOT  | Present work                |
| **GRB 130603B**|             |                |        |           |                             |
| 05.06.2013    | 5x300        | 20.69 ± 0.15   | I      | 1.5m OSN  | Pandey et al. (2019)        |
| 22.06.2013    | 15x60        | 19.69 ± 0.13   | K      | 3.5m CAHA | Pandey et al. (2019)        |
| 22.06.2013    | 15x60        | 20.06 ± 0.09   | J      | 3.5m CAHA | Pandey et al. (2019)        |
| 22.06.2013    | 15x60        | 19.68 ± 0.13   | H      | 3.5m CAHA | Pandey et al. (2019)        |
| 22.06.2013    | 15x60        | 20.11 ± 0.07   | Z      | 3.5m CAHA | Pandey et al. (2019)        |
| 05.07.2013    | 4x50         | 22.01 ± 0.03   | g      | 10.4m GTC | Pandey et al. (2019)        |
| 05.07.2013    | 4x50         | 20.97 ± 0.01   | r      | 10.4m GTC | Pandey et al. (2019)        |
| 05.07.2013    | 4x50         | 20.65 ± 0.02   | i      | 10.4m GTC | Pandey et al. (2019)        |
| **23.03.2017**| **2x300**    | **22.13 ± 0.05**| B      | 3.6m DOT  | Present work                |
| **23.03.2017**| **2x300**    | **20.72 ± 0.02**| R      | 3.6m DOT  | Present work                |
| **GRB 140102A**|             |                |        |           |                             |
| 13.05.2014    | 59x65.0      | 21.18 ± 0.26   | H      | CAHA      | Gupta et al. (2021a)        |
| 18.07.2017    | 7x120.0      | 25.13 ± 0.16   | g      | 10.4m GTC | Gupta et al. (2021a)        |
| 18.07.2017    | 7x90.0       | 24.47 ± 0.13   | r      | 10.4m GTC | Gupta et al. (2021a)        |
| 18.07.2017    | 7x90.0       | 24.17 ± 0.13   | i      | 10.4m GTC | Gupta et al. (2021a)        |
| 18.07.2017    | 6x60.0       | 23.88 ± 0.18   | z      | 10.4m GTC | Gupta et al. (2021a)        |
| **16.01.2021**| **3x300.0, 2x900.0** | ≥ 24.10 | R      | 3.6m DOT  | Gupta et al. (2021a)        |
| **GRB 190829A**|             |                |        |           |                             |
| 26.09.2000    | –            | 18.64 ± 0.05   | u      | SDSS      | Abazajian et al. (2005)     |
| 26.09.2000    | –            | 16.86 ± 0.005  | g      | SDSS      | Abazajian et al. (2005)     |
| 26.09.2000    | –            | 15.729 ± 0.004 | r      | SDSS      | Abazajian et al. (2005)     |
| 26.09.2000    | –            | 15.229 ± 0.004 | i      | SDSS      | Abazajian et al. (2005)     |
| 26.09.2000    | –            | 14.872 ± 0.007 | z      | SDSS      | Abazajian et al. (2005)     |
| 12.12.2000    | –            | 13.798 ± 0.096 *| J    | 2MASS     | Skrutskie et al. (2006)     |
| 12.12.2000    | –            | 12.877 ± 0.092 *| H    | 2MASS     | Skrutskie et al. (2006)     |
| 12.12.2000    | –            | 12.320 ± 0.104 *| K    | 2MASS     | Skrutskie et al. (2006)     |
| **03.10.2020**| **2x300**    | **17.05 ± 0.05**| B      | 3.6m DOT  | Present work                |
| **03.10.2020**| **2x200**    | **15.75 ± 0.02**| R      | 3.6m DOT  | Present work                |
| **03.10.2020**| **2x200**    | **15.26 ± 0.03**| I      | 3.6m DOT  | Present work                |
| **GRB 200826A**|             |                |        |           |                             |
| 28.08.2020    | 3600         | 21.11 ± 0.16   | J      | Palomar Hale 200-in (P200) | Ahumada et al. (2021) |
| 13.09.2020    | 5x180        | 23.45 ± 0.24   | u      | 4.3m LDT  | Ahumada et al. (2021)       |
| 13.09.2020    | 4x180        | 23.36 ± 0.05   | g      | 4.3m LDT  | Ahumada et al. (2021)       |
| 13.09.2020    | 10x150       | 22.86 ± 0.18   | r      | 4.3m LDT  | Ahumada et al. (2021)       |
| 13.09.2020    | 6x180        | 22.13 ± 0.05   | z      | 4.3m LDT  | Ahumada et al. (2021)       |
| **04.11.2020**| **12x300**   | **22.71 ± 0.10**| i      | 3.6m DOT  | Present work                |
| **04.11.2020**| **2100**     | > 20.56*       | J      | 3.6m DOT  | Present work                |
| **11.11.2020**| **2100**     | > 19.55*       | K      | 3.6m DOT  | Present work                |