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Measurement methods for gamma-ray bursts redshifts

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In the era of multi-messenger astronomy, gamma-ray bursts (GRBs) with known redshifts, especially high-redshift GRBs, are a powerful tool for studying the structure and evolution of the early Universe. We review the background, the history, and the application of measurement methods of GRB redshifts in astronomy. Based on different observation targets, two measurement methods are mainly introduced. One is on GRB afterglow, the other is on GRB host galaxy. There are various processing methods belonging to measurement methods based on afterglow, including spectral measurement method of afterglow and afterglow spectral energy distribution fitting method with improved methods. There are also numerous measurement methods based on host galaxy, such as spectral measurement method of host galaxy, template matching method of host galaxy, some automatic spectroscopic redshift measurement methods, and machine learning methods. We subsequently introduce the principles, effects, and performance of these methods. We enumerate several detection and measurement instruments, which have been used in observation. The characteristics, advantages, disadvantages, and applicability of the GRB redshift measurement methods are summarized and analyzed. Furthermore, we provide a data set of 611 GRBs with measured redshift. The data set has been collected since 1997. Analysis and statistics are presented based on this data set. We summarize the characteristics of GRBs such as location, time, and accuracy. Finally, we introduce Space-based multi-band astronomical Variable Objects Monitor (SVOM) mission dedicated to searching high redshift GRBs. We also introduce the application prospect of various redshift measurement methods in SVOM mission.

KEYWORDS

gamma-ray bursts, redshift, measurement methods, afterglow, host galaxy

1 Introduction

In the era of multi-messenger astronomy, the redshifts of gamma-ray bursts (GRBs) have been widely used in many research fields of astronomy because they can be observed up to z ≈ 8–9 (Salvaterra et al., 2009; Cucchiara et al., 2011). We note that their redshifts distribution has a peak at z ∼ 2 (Coward et al., 2013) which approximately corresponds to the distance of the farthest SNe-Ia ever detected (Rodney et al., 2015). Therefore, today we can state, without fear of contradiction, that GRBs have become an important tool for the study of cosmology as a whole (Salvaterra, 2015). At present, GRB redshift shows its importance in the study of cosmological parameters (Amati et al., 2008; Amati and Della Valle, 2013; Izzo et al., 2015; Moresco et al., 2022), dark energy with GRBs (Muccino et al., 2021), core-collapse supernovae (SNe) and GRB connection (Woosley and Bloom, 2006; Kelly et al., 2008), SNe emerging from the lightcurve afterglows (Della Valle et al., 2006; Melandri et al., 2019), GRBs hosts (Modjaz et al., 2008; Fruchter et al., 2006; Savaglio et al., 2009).

Redshifts are used to derive GRB parameters, such as $E_{p,i}$, E_{iso}, *etc.* At present, the correlations of GRB parameters are often used to measure cosmological parameters Ω_M and Ω_Λ. The results are high-precision and independent by parameters of other cosmological detectors such as SN Ia. Amati and Della Valle (2013) have measured Ω_M with $E_{p,i} - E_{iso}$ correlation and obtained (for a flat Universe) that the Ω_M is in the range 0.14–0.57. The same analysis carried out on a larger sample, found $\Omega_M \sim 0.3$ (Amati and Della Valle, 2013), which is consistent with $\Omega_M = 0.29^{+0.23}_{-0.15}$ obtained by Izzo et al. (2015) by using $E_{\gamma,iso} - E_{x,iso} - E_{pk}$ parameters. More recently Moresco et al. (2022) measured for a flat Universe $\Omega_M = 0.26^{+0.23}_{-0.12}$ using the $E_{p,i} - E_{iso}$ correlation.

GRBs are suitable for studying the possible evolution of the equation from the state of the Universe when we consider the intermediate redshift case. The parameter $w(z)$ of dark energy will be affected by GRB redshift. According to GRB Hubble diagram, the evolution of $w(z)$ has different piecewise formulae in different redshift intervals. When $z \leq 1.2$, Muccino et al. (2021) found that $w = -1$, and the deviation of $w(z)$ was within 1σ. With the increasing of z, the value of $w(z)$ is better determined, but $w(z)$ seems to have a strong deviation more than 2σ.

The GRB redshifts and light curves of afterglows are helpful to study the relationship between SN and GRB. By studying the GRB and SN at different redshifts, it is found that not all SNe connect with GRBs (Woosley and Bloom, 2006). It is predicted that SN associated with GRB has basically no optical flux at $z > 1.2$. For example, the GRB 050525A has the redshift of spectrum $z = 0.606$. The shape and fluxes of the light curve confirmed that SN 2005nc was formed in the late afterglow of GRB 050525A (Della Valle et al., 2006). GRB 171010A and SN 2017htp (Melandri et al., 2019) have the same redshift at $z = 0.33$. This is another example that SN is connected with GRB.

GRB redshifts are helpful to study the physical characteristics of the host population. The spectra of GRB host galaxies with different redshifts are studied, and the characteristics of chemical abundance are obtained (Modjaz et al., 2008). Long GRBs (LGRBs) are more concentrated in the bright regions of the host galaxy than Core Collapse SNe (Fruchter et al., 2006) and seem to share the same locations as SNe-Ic (Kelly et al., 2008). In addition, the host galaxies of LGRBs are much dimmer and more irregular than those of core-collapse supernovae. The results show that LGRBs are related to the massive stars, and may be confine to chemical evolution. Most of the high redshift LGRB hosts are irregular with no bulges (Kelly et al., 2008). The optical-near infrared (NIR) photometry and spectroscopy are used to deduce the star mass, star formation rates (SFRs), dust extinction, and metal abundance of GRB host galaxy (Savaglio et al., 2009).

Some GRB detection instruments are working or being built, such as Gamma-Ray Burst Optical and Near-Infrared Detector (GROND) (Greiner et al., 2008), Swift (Gehrels et al., 2004), Fermi Gamma Ray Space Telescope (Atwood et al., 2009; GLAST Facility Science Team et al., 1999), Space-based multi-band astronomical Variable Objects Monitor (SVOM) (Wei et al., 2016) and so on.

In Section 2, we introduce the history of GRB redshift measurement. The redshift measurements of GRB 970228 and GRB 970508 (the first and second GRBs with known redshift) are emphatically reviewed. In Section 3, we mainly summarize two kinds of common measurement methods of GRB redshift, including the measurement methods based on afterglow and the measurement methods based on host galaxy. The principles, advantages, disadvantages of different methods are introduced. In Section 4, we gather 611 GRBs with redshifts since 1997. We make a statistical analysis of the data, and summarize the characteristics of GRBs, such as location, time and accuracy. We verify the application of different methods introduced above. The advantages and disadvantages are also been presented. In Section 5, we present the summary in this review. We prospect a future space mission SVOM and new GRB redshift measurement methods.

2 The history of GRB redshift measurement

The GRB redshift measurement began in 1997. On 28 February 1997, BeppoSAX satellites detected GRB 970228 and its X-ray afterglow (Costa et al., 1997; Sahu et al., 1997). The optical afterglow of GRB 970228 was also observed to obtain photometric and spectroscopic data by William Herschel Telescope (WHT), Bologna University Telescope (BUT), Rome Astro Physical Observatory (ROA), and other telescopes (Van Paradijs et al., 1997; Galama et al., 1997). The observed photometric data and images are used for theoretical interpretation and modeling analysis (Wijers et al., 1997). Moreover, an extended nebula region was found and determined as the host of GRB 970228 (Galama et al., 1997; Fruchter et al., 1999). Keck II telescope with a low-resolution spectrometer was used to observe host galaxy of GRB 970228 several times. There are two strong emission lines, which are identified as [O II] λ3727 and [O III] λ5007, and a weak emission line [Ne III] λ3869 in the spectrum of the host galaxy. However, the low resolution of the instrument makes it impossible to distinguish the double peaks of [O II] λ3727. The strong OH line in the night sky also interferes with the measurement of $H\beta$ λ4861, [O III] λ4959 and the higher Balmer line. Despite the influence of the above factors, the redshift of GRB 970228 can still be derived as $z = 0.695 \pm 0.003$ by the spectral measurement method of host galaxy. The redshift confirms GRBs lie at cosmological distance (Bloom et al., 2001a).

On 8 May 1997, BeppoSAX satellite detected GRB 970508 (Metzger et al., 1997b; Sahu et al., 1997). Subsequently, its multi-waveband afterglow was observed, and relatively complete afterglow data were derived (Reichart, 1998). Metzger et al. (1997b) estimated the redshift range by spectral measurement from optical afterglow. Spectrum of optical afterglow OT J065349+79163 were obtained using Keck II 10-m telescope with low-resolution imaging spectrometer. The spectrum contains eight strong absorption lines of Fe II, Mg II and Mg I systems. By calculating the independent redshift for each absorption line, and considering the interference of gas clouds, a strict lower limit for the redshift of the source was set as $z \geq 0.835$. An approximate upper limit ($z \leq 2.3$) was set for the characteristic that no obvious Lyman-α absorption line in the spectrum. To sum up, the redshift range of GRB 970508 is $0.835 \leq z \leq 2.3$. Reichart (1998) used the photometric data of GRB 970508 optical afterglow to fit the optical spectral energy distribution SED, and used χ^2 fitting to get the redshift $z = 1.09^{+0.14}_{-0.41}$. In addition, Metzger et al. (1997a) and Fruchter et al. (1997) predicted that the host galaxy of GRB 970508 is a dark galaxy with $z \geq 0.835$. Bloom et al. (1998) obtain the photometric and spectroscopic data of the host galaxy from Keck II telescope, and measured a more accurate redshift. There is a strong emission line at $\lambda_{obs} = 6839.7 Å$ and a weak emission line at $\lambda_{obs} = 7097.7 Å$ in the spectrum. Then, the two emission lines are identified as [O II] λ3727 and [Ne III] λ3869 lines. Finally, the redshift calculated by weighted average is $z = 0.8349 \pm 0.0003$. The spectral measurement of GRB 970508 also confirmed the cosmological GRB (Metzger et al., 1997b).

Subsequently, more and more GRBs with redshifts have been measured, such as GRB 970828 at $z = 0.9579$ (Djorgovski et al., 2001), GRB 971214 at $z = 3.42$ (Kulkarni et al., 1998), GRB 980326 at $z \sim 1$ (Bloom et al., 1999), *etc.* After the Swift satellite was launched in 2004, the number of measured GRBs redshifts greatly increased (Lin, 2009). High redshift GRBs can be detected. At present, GRB redshift ranges from $z = 0.0085$ (GRB 980425) (Galama et al., 1998) to $z \sim 9.4$ (GRB 090429B) (Cucchiara et al., 2011). Especially, a few GRBs with $z \geq 6$ have been detected, such as GRB 080913 at $z = 6.7$ (Greiner et al., 2009a), GRB 090423 at $z \sim 8.2$ (Tanvir et al., 2009), GRB 120521C at $z \sim 6$ (Laskar et al., 2014), GRB 120923A at z ~7.8 (Tanvir et al., 2018). High-redshift GRBs are considered as a new and powerful tool to explore the early Universe (Wei et al., 2015). As LGRBs are related to the death of massive stars. They can be born in the interstellar matter (ISM) of primordial galaxies, and unique probes in the re-ionization era (Heintz et al., 2019; Tanvir et al., 2019; Saccardi et al., 2023). In principle, GRB afterglow can be detected at $z \sim 20$ (Ciardi and Loeb, 2000; Gou et al., 2004). The early Universe with z = 6–20 is the crucial period in cosmology at present (Wei et al., 2015).

3 Measurement methods of GRB redshift

Based on different observation targets, two types of measurement methods are mainly introduced. One is on GRB afterglow, the other is on GRB host galaxy. Besides, we also introduce a pseudo-redshift estimation method without redshift measurement.

Based on the principles and characteristics of different measurement methods summarized in Section 3.1–3.3, we summarize the applications of different measurement methods. We also present a comparison of the advantages and disadvantages of each method in Table 1.

3.1 Measurement methods based on afterglow

The GRB prompt emission duration is extremely short, usually between a few milliseconds and a few minutes. GRB afterglow is occurring later than prompt emission and lasts longer time, so is beneficial for target tracking and observation. Among them, X-ray and optical afterglow emission can last for several days to several weeks, and radio afterglow radiation can last for several years (Zhang, 2007). At present, the afterglows used to measure GRB redshifts are generally in optical, NIR and ultraviolet bands. In the BeppoSAX era, GRB redshifts were measured by the emission lines of X-ray afterglow (Antonelli et al., 2000). In principle, Swift/XRT can be used to measure the redshift with Fe line emission (Burrows et al., 2003). However, Swift never measured the redshift by using the X-ray emission line in observation.

The advantage of afterglow measurement is that afterglow is usually brighter than the host galaxy (Curran et al., 2008). The spectrum and photometry data of afterglow can be obtained. Compared with galaxy optical lines, many prominent absorption lines in the afterglow are bluer. Thus, GRB afterglow at higher redshift can be measured in optical spectroscopy of afterglows. For example, Lyman-α absorption line in GRB afterglow is one of the most important features for redshifts measurement in the case of $z > 2$. In the case of $z \sim 3$, there are many prominent interstellar absorption lines of Mg II, Mg I, Ca II, Fe II often seen in optical spectrum. These absorption lines have rest wavelengths in the 2,000–4,000$Å$ range. By contrast, usually the bluest emission line O II of the GRB host galaxy is at 3,727 $Å$. So, the common emission lines of the GRB host galaxy are in the optical band at $z = 0$. The emission lines at $z > 1.5$ tends to be beyond the range of most optical spectrometers. On the other hand, the GRB afterglow continuous spectrum is usually described as a simple power law. The GRB afterglow is typically affected by Lyman-α forest and dust extinction, in addition to discrete absorption lines from the host and any intervening absorbers (Curran et al., 2008). Lyman-α and Lyman-break features are prominent features, which are included in the GRB afterglow continuous spectrum (Krühler et al., 2011b). The spectral energy distribution of GRB afterglow, basically described as a smooth power law, is simpler than that of host galaxy. The absorption features of GRB afterglows have a fairly predictable range and less uncertainty. By contrast, galaxy spectra are very complex, which are the superposition of light from stars, nebulae, and the absorption from interstellar medium. At $z \geq\sim 2.5$ where the Lyman-α break passes through the u band, the photometric redshifts measurement for GRBs are more robust than galaxy photometric redshifts measurement. The measurement methods based on GRB afterglow are more suitable for high-redshift GRB determination. It indicates that the optical afterglow is dark (Mirabel and Rodrigues, 2003; Roming et al., 2006a). The optical afterglow measurement can be affected by the local GRB environment, the type of host galaxy, and other related extinction factors (Coward et al., 2008). Thus, it makes an ineffective redshift measurement.

3.1.1 Spectral measurement method of afterglow

GRB Redshift measurement usually relies on optical and NIR spectroscopy in the medium and large telescopes (Tanvir and Jakobsson, 2007). The observation spectrum

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TABLE 1 Advantages, disadvantages and applicability of different measurement methods of GRB redshift

Method		Advantages	Disadvantages	Applications
Measurement methods based on afterglow	Spectral measurement method of afterglow	High precision; Afterglow is brighter than the host, high quality and high redshift spectrum can be obtained.	Long exposure time; Affected by noise; If the afterglow decays too fast, it will affect the accuracy.	GRBs with slow afterglow decay, high luminosity; No detected host galaxy.
	Afterglow spectral energy distribution fitting method	The principle is simple; The speed is fast; The exposure time is short; GRBs with low luminosity and high redshift can be measured.	Low precision; The GRBs have great individual differences, so it is difficult to obtain a complete model.	GRBs with high redshift; Dark afterglow; No detected host galaxy.
Measurement methods based on host galaxy	Spectral measurement method of host galaxy	High precision; Long exposure and multiple observations can be allowed.	The host galaxy is dark, which affects the quality of spectral lines; There may be multiple candidates, which will affect the accuracy.	Dark Bursts; Low redshift GRB
	Automatic spectroscopic redshift measurement methods	High precision; Automatic redshift measurement; Fast speed; High efficiency	Some targets have large errors, which can't reach the precision of manual measurement; Template needs to be established; Complex algorithm	Rapidly determine the redshift range of multiple host candidates
	Template matching method of host galaxy	The speed is fast; The exposure time is short; The intra-class difference of galaxies is small, the SED template is relatively standard, dark high-redshift galaxies and outside the spectral measurement limit can be observed.	Low precision; No universal SED template; Multiple candidates, which will affect the accuracy.	Dark Bursts; Dark host galaxies; GRBs with relatively high redshift in host galaxies.
	Machine learning	High precision; Automatic redshift measurement; Fast speed; Good robustness; Strong fault tolerance; High efficiency	A training set that requires spectral redshift; Complex algorithm	Rapidly determine the redshift range of multiple host candidates
Pseudo-redshift estimation method	Luminosity-indictor relationships	The estimation method is independent of observed real redshift; Not affected by the redshift selection effect; Get larger amount of redshift data than obversed.	Affected by correlation; Large errors	Popular in early research; It is suitable for GRBs with strong correlation of photometric indexes; Compared with other methods, it is less used at present.

is matched with laboratory spectrum. Usually, GRB optical afterglow do not show emission lines.[1] We can compare one observed line of the spectrum to the line in the laboratory spectrum, and the weighted average operation is performed to derive spectroscopic redshift value of the target. The method was applied in GRB 060714 ($z = 2.711$) (Fynbo et al., 2009; Jakobsson et al., 2006a), GRB 080210 ($z = 2.6419$) (Fynbo et al., 2009), GRB 210905A ($z = 6.312$) (Rossi et al., 2022).

The accuracy of the measured redshift is high, up to about 10^{-4}. However, the signal-to-noise ratio of absorption line can affect the accuracy of spectroscopic redshift. The optical afterglow is too fast to have a sufficient bright spectrum. Due to some optical afterglow decaying in a short time, and the brightness is insufficient. Thus, the spectrum with strong absorption may not be obtained.

Spectral measurement method of afterglow is suitable for relatively bright GRBs with slow delay. In fact, as long as one GRB has bright afterglow, when a clear spectrum can be obtained, the very high redshift of target can be measured. For example, GRB 090423 has a high redshift of $z \sim 8$ (Salvaterra et al., 2009; Tanvir et al., 2009; Oates and Cummings, 2009). Due to the bright near-infrared afterglow and no counterpart at optical wavelengths, Tanvir et al. (2009) used the ISAAC spectroscopy and VLT spectroscopy by spectral measurement method of afterglow, as well as the photometric data to derive the redshift of $z = 8.23^{+0.06}_{-0.07}$. Salvaterra et al. (2009) used TNG to derive the spectroscopic redshift of $z = 8.1^{+0.1}_{-0.3}$.

The common instruments for measuring afterglow spectrum include Keck, VLT, GTC and so on. Due to the limitation of the atmosphere, the occurrence time and the position of the source in the sky, in a few cases, the afterglow spectrum can be obtained by using ground near-ultraviolet equipment such as VLT-UVES(Fiore et al., 2005; Vreeswijk et al., 2007). Ultraviolet afterglow can also be detected by Swift/UVOT (Kuin et al., 2009) to measure redshift.

3.1.2 Afterglow spectral energy distribution fitting method (photometric redshift measurement of afterglow)

We used spectral energy distribution (SED) fitting method of GRB afterglow to obtain photometric redshift. The medium and small aperture telescopes are used to perform photometric observations of the afterglow in multi-bands. Then SED fitting method is used to estimate the photometric redshift of target. Some templates are necessary for SED fitting method. The synthetic template is compared with the observed data, so that it can be reasonably extrapolated to the unmeasured redshift range. When χ^2 is the smallest, the redshift of target is considered (Bolzonella et al., 2000). X-ray and optical afterglows are usually used, and the SED shape depends on cooling frequency (ν_c), optical frequency (ν_o) and X-ray frequency (ν_x) (Japelj et al., 2015; Zaninoni et al., 2013). The SED includes two prominent features, Lyman-α and Lyman Break at $121.5(1+z)$ nm and $91.2(1+z)$ nm respectively, and GRB redshift measurement mainly depends on them (Krühler et al., 2011b).

When $\nu_c < \nu_o$ or $\nu_c > \nu_x$, the SED can be described with a single power-law as Eq. 1

$$F_\nu = F_0 \nu^{-\beta_{O,X}} \tag{1}$$

Where ν is the observed frequency, $\beta_{O,X}$ the spectral index and F_0 the normalization.

And, when $\nu_o < \nu_c < \nu_x$, the SED can be described with a broken power-law as Eq. 2

$$F_\nu = F_0 \begin{cases} \nu^{-\beta_O} & \nu \le \nu_c \\ \nu_c^{\Delta\beta}\ \nu^{-\beta_X} & \nu > \nu_c \end{cases} \tag{2}$$

Where $\Delta\beta = \beta_X - \beta_O$.

At present, Hyperz, New Hyperz, *etc.*, are usually used to fit SED (Cucchiara et al., 2011; Afonso et al., 2011; Zaninoni et al., 2013; Rossi et al., 2008). The dust extinction laws in the Milky Way (MW), Small Magellanic Clouds (SMC) and Large Magellanic Clouds (LMC) are added to the synthetic template. This method was applied in GRB 050814 ($z = 5.3 \pm 0.3$) (Jakobsson et al., 2006b), GRB 070802 ($z = 2.47^{+0.18}_{-0.15}$) (Krühler et al., 2008), GRB 080514B ($z = 1.8^{+0.4}_{-0.3}$) (Rossi et al., 2008), GRB 090429B ($z \sim 9.4$) (Cucchiara et al., 2011), GRB 120521C ($z = 6.01^{+0.05}_{-0.09}$) (Laskar et al., 2014).

In order to make the characteristics of the synthetic template approach to the real afterglow, some improved SED fitting methods are proposed. Curran et al. (2008) simulated the absorption effect caused by Lyman forest and host extinction, and used both a genetic algorithm-based routine and Monte Carlo error analysis to simultaneously fit the parameters of interest. Japelj et al. (2015) corrected the MW extinction laws and photoelectric absorption. Littlejohns et al. (2014) increased the host dust extinction and the neutral hydrogen effect along the line of sight. Krühler et al. (2011b) considered several systematic uncertainties, including the uncertainty in the dust redding properties, the opacity of the Lyman-α forest, and the strength of the Damped Lyman-α Absorber (DLA) associated with the GRB. All the above methods are reliably to derive the GRB photometric redshift. The cases are GRB 050904 ($z = 6.61 \pm 0.14$) (Curran et al., 2008), GRB 100905A ($z = 7.88^{+0.75}_{-0.94}$) (Bolmer et al., 2018), GRB 191016A ($z = 3.29 \pm 0.4$) (Smith et al., 2021).

Compared to spectroscopic redshift, the accuracy of photometric redshift is lower. Greiner et al. (2008) proposed that the error of GRB photometric redshift is in $\Delta z \sim 0.3$–0.5. Krühler et al. (2011b) proposed that the best result is $\eta = \frac{\Delta z}{1+z} \sim 0.03$. By comparing GRBs with known spectroscopic redshift, the accuracy of photometric redshift is lower than that of spectroscopic redshift derived by using a low-resolution spectrometer, about 10^2–10^3 error.

Each GRB has certain individual differences. Thus, a standard template is difficult to meet the characteristics of all GRBs. However, photometric measurement is suitable for relatively optical-NIR GRB afterglow.

Some common telescopes for photometric measurements are GROND, Robotic Optical Transient Search Experiment (ROTSE-III), Rapid Eye Mount telescope (REM). In addition, Swift/UVOT are also perform for the photometric measurement. When Lyman-α

1 The point is quoted from anonymous reviewers' comments.

and Lyman-break pass into the filter ranges, accurate GRB photometric redshift can be derived. In other words, with different redshifts, Lyman features enter different filters. For example, redshift sensitivity to Lyman-α cutoff between UVW2 band (central wavelength $\lambda_c = 188$ nm) and UVM2 band ($\lambda_c = 217$ nm) is $z \sim 1.3$, between UVM2 band and UVW1 band ($\lambda_c = 251$ nm) is $z \sim 1.7$, between UVM1 band and U band ($\lambda_c = 345$ nm) is $z \sim 2.3$, between U band and B band ($\lambda_c = 439$ nm) is $z \sim 3.2$, between B band and V band ($\lambda_c = 544$ nm) is $z \sim 3.5$ (Krühler et al., 2011b; Roming et al., 2005).[2] Lyman-break falls from g' band ($\lambda_c = 468.6$ nm) to z' band ($\lambda_c = 893.1$ nm) at $3.5 < z < 6.5$, and from z' band to J band ($\lambda_c = 1.25\ \mu m$) at $z \sim 8$. Afterglows are only detected in H band ($\lambda_c = 1.65\ \mu m$) or Ks band ($\lambda_c = 2.16\ \mu m$) at $z \sim 10$ (Krühler et al., 2011b; Greiner et al., 2008; Skrutskie et al., 2006; Abazajian et al., 2009).[3]

It appears that targets with different redshift ranges can be measured using different filter bands. The measurable redshift range of Swift/UVOT is $0.5 < z < 3.5$ (Kuin et al., 2009), covering the 170–600 nm wavelength, and the measurable redshift range of GROND is $3.5 \leq z \leq 13$ (Greiner et al., 2008), covering the 360–2,300 nm wavelength. Therefore, multiple devices are often used for combined measurement.

3.2 Measurement methods based on host galaxy

Host galaxy provides important information on the GRB environment. GRB host has the individual differences. For example, the host of GRB 970228 is essentially a face-on late-type blue dwarf galaxy (Bloom et al., 2002), GRB 970508 is in a compact, elongated and blue galaxy (Bloom et al., 2002), GRB 980425 is suspected to be in a nearby spiral galaxy (Conselice et al., 2005), the host galaxy of GRB 981226 appears to have a doubly nucleated morphology (Bloom et al., 2002), GRB 000418 is in a compact galaxy (Bloom et al., 2002).

By the statistical analysis, GRB hosts, which have been observed, are usually young, blue and low-redshift, in addition to low mass and low metallicity (Savaglio et al., 2009) (Perley et al., 2016b). But there are also a few GRBs, especially Dark Bursts, found in massive, metal-rich and high-redshift galaxies (Krühler et al., 2012; Perley et al., 2016b). Due to the correlation between mass and metallicity, GRB host galaxies have lower luminosity and smaller sizes than typical galaxies (Le Floc'h et al., 2003; Fruchter et al., 2006). Bloom et al. (2002) found that the hosts are compact and blue with high central surface brightness, when GRBs are found nearby their host centers. Svensson et al. (2010) found that GRB hosts are always fainter than those of SN counterparts, due to the low metallicity of the GRB host. Moreover, GRB hosts are irregular, small, low mass with more actively star forming. Perley et al. (2016b) found that NIR luminosities of hosts are rapidly increase in low redshift range ($0.5 < z < 1.5$). However, they are almost unchanged in mid-high redshift ($1.5 < z < 5$). The low-redshift hosts are fainter than tracers with star formation uniformly, and the mid-high redshift hosts are similar to tracers. At low redshift, there is almost no GRB in massive galaxies.

Short GRBs (SGRBs) originate from the mergers of compact objects, such as binary neutron stars mergers and neutron star-black holes mergers (Fruchter et al., 2006; Nugent et al., 2022). About 84% of SGRB hosts are star-forming galaxies (Nugent et al., 2022). The hosts of SGRB have SFRs consistent with their stellar masses, which is about 1.44 $M_{\odot} yr^{-1}$. They have usually a wide age range ($\sim$0.1 – 9 Gyr) with low redshift (Nugent et al., 2022; Berger et al., 2005; Barthelmy et al., 2005).

LGRBs are usually found in extremely blue galaxies with strong emission lines, indicating that this is an apparent abundance of young and massive stars (Fruchter et al., 2006). LGRB hosts are mainly irregular galaxies with low mass, and they have relatively higher redshift median than SGRB hosts (Lyman et al., 2017). Only a few LGRBs are found in spiral galaxies (Fruchter et al., 2006; Conselice et al., 2005). LGRB hosts with low redshifts have higher concentration and lower luminosity than high redshift hosts (Lyman et al., 2017). LGRBs are centrally concentrated, strongly biased towards the brighter regions in hosts. It is found that LGRB hosts are fainter than SFR-weighted field galaxy populations at the same redshift.

The advantage of host galaxy redshift measurement is that hosts have constant luminosity. Unlike the rapidly fading afterglow, the GRB host galaxy can be detected by increasing the exposure time, so that we can obtain more accurate spectrum and photometric data. Host galaxy can be detected many times in a long-time range, reducing the measurement error. At low redshift, Lyman-break may not enter into the photometric bands of UVOT, so the spectral features of afterglow are not clear. The host galaxy measurement is more suitable for low redshift GRB. For "Dark Burst", where optical afterglow is hardly observed (O'Connor et al., 2022), measurement methods based on host galaxy are important tools to derive redshift.

Some GRBs host galaxies are failed to be detected. It is because some GRBs were kick out from the host galaxies before the bursts (Bloom et al., 2002), or the GRBs have a high redshift and the host galaxy are too dark to be detected. Several candidate galaxies are near the GRB position, so it is difficulty to identify host. In addition, due to the influence of "Redshift Desert", the lack of strong emission lines affects the measurement of GRB with $z = 1$–2 (Fiore et al., 2007).

3.2.1 Spectral measurement method of host galaxy

The principle of host galaxy spectral measurement is the same as the normal galaxy. By comparing the observed lines with spectral lines in the laboratory, the spectroscopic redshift of GRB can be derived. GRB hosts are usually star-forming galaxies, and they show the strong emission lines (Jakobsson et al., 2012; Krühler et al., 2015), such as [O II] λ3727, $H\beta$ [OIII] λ5007 and $H\alpha$, in addition to weak emission lines [Ne III] [NIII], *etc.* Krühler et al. (2015) build a comprehensive sample of GRB host emission line spectrum. In the spectra, the superposition fitting of the Gaussian function to the data is effective to get the fluxes of strong emission lines. For weak emission lines, it is necessary to tie the Gaussian centroid and linewidth to those of strong lines. The method was applied in GRB 050714B ($z = 2.4383$) (Krühler et al., 2015),

2 The bands please see https://swift.gsfc.nasa.gov/about_swift/uvot_desc.html

3 g'r'i'z' filters please see https://classic.sdss.org/dr5/

GRB 060923B ($z = 1.5094$) (Krühler et al., 2015), GRB 080905A ($z = 0.1218$) (Rowlinson et al., 2010), GRB 101224A ($z = 0.4536$) (O'Connor et al., 2022), GRB 180805B ($z = 0.6609$) (O'Connor et al., 2022), GRB 211211A ($z = 0.0763$) (Rastinejad et al., 2022).

Spectral measurement method of host galaxy has high accuracy. GRB host has constant luminosity. Unlike the rapidly fading afterglow, they can be observed with a high-precision spectrometer for long exposure time. However, some host galaxies are faint, so that we cannot detected the spectral lines with high signal-to-noise ratio. Moreover, some GRB host galaxies at high redshift are not detected. Therefore, spectral measurement method of host galaxy is suitable for low redshift GRBs. We can also use this method to detect "Dark Burst" redshift. Some large telescopes, such as VLT/X-shooter, Keck, Magellan, are used for this method.

3.2.2 Automatic spectroscopic redshift measurement methods

Some GRB host galaxies are nearby galaxies. They are blue, low mass and low metallicity. Almost all the observation techniques and data processing techniques for studying other distant galaxies can be used to GRB host galaxies (Antonelli et al., 2000). At present, astronomers manually compare the observed spectral lines to the spectral lines in the laboratory. This way is inefficient.

By Automatic spectroscopic redshift measurement methods, we can automatically measure, identify and verify spectral lines, and use template matching method to derive redshift. There are many methods we can consider adopting. They are cross-correlation (Tonry and Davis, 1979), PCAZ (Glazebrook et al., 1998), pseudo-triangle (Qiu et al., 2002), wavelet technique to measure spectral lines and identify Balmer jump points (Luo and Zhao, 2001), density estimation (Duan et al., 2005), Hough transform (Zhou et al., 2000), Bayesian convolution network (Xu et al., 2006a), similarity measurement (Liu et al., 2008), nonlinear dimension reduction (Xu et al., 2006b), Parzen window (Tu et al., 2012), multi-resolution fusion distance method (Pan et al., 2016).

Compared with the number of normal galaxies, the number of GRB hosts is much less, and they are spread over the sky and randomly distributed. Therefore, it is hard to observe one GRB host from astronomy sky surveys. But automated algorithms still have some advantages. Automated algorithms may improve efficiency compared to traditional processing methods. It was presented that the automatic spectroscopic redshift measurement methods have high accuracy. The 97% goal can get the same result as manual processing (Zhu et al., 2005). These methods have fast processing speed, and can automatically process low signal-noise-ratio spectrum (Pan et al., 2016; Zhu et al., 2005). When GRB host is identified, the automatic algorithm can rapidly and accurately measure the redshift. Moreover, the automatic algorithm can quickly determine the redshift interval of each candidate and make a rough classification when the GRBs have multiple candidate hosts. Thus, one or more unqualified candidates can be quickly eliminated and the observation cost can be reduced.

3.2.3 Template matching method of host galaxy

Template matching method of host galaxy can measure the photometric redshift of target by SED fitting. Compared with GRB afterglow, the physical model of host galaxy is more complex, which should have considered isochron, star spectrum, initial mass function (IMF), star formation history, and chemical evolution (Johnson et al., 2021). At present, some popular codes for SED fitting are GALAXEV (Bruzual and Charlot, 2003), PGase (Maraston, 2005), FSPS (Conroy et al., 2009), BPASS (Eldridge et al., 2017). We can compare the template with the observation data. When the likelihood function is minimum, the photometric redshift is derived. Some Matching methods are Bayes (Salim et al., 2007), Hyperz (Bolzonella et al., 2000), EAZY (Acquaviva et al., 2015), CIGALE (Burgarella et al., 2005), MAGPHYS (Cunha et al., 2008), MCMC (Acquaviva et al., 2012), GalMC (Acquaviva et al., 2011), BEAGLE (Chevallard and Charlot, 2016), BAGPIPES (Carnall et al., 2018), LePHARE (Gupta et al., 2021), Prospector (Johnson et al., 2021). The method was applied in GRB 000214 ($z = 0.49^{+0.05}_{-0.07}$) (Guziy et al., 2005), GRB 191031D ($z = 0.5 \pm 0.2$) (O'Connor et al., 2022), GRB 200411A ($z = 0.6 \pm 0.1$) (O'Connor et al., 2022).

At present, there is no universal SED template due to the diverse features of galaxies (Gupta et al., 2022). Due to the uncertainty of photometric measurement, the accuracy of template matching method of host galaxy is relatively low. However, some GRB host galaxy are faint, so absorption lines and emission lines cannot be distinguished in some galaxy spectra. Photometric measurement is particularly useful for observing faint and relatively high redshift galaxies.

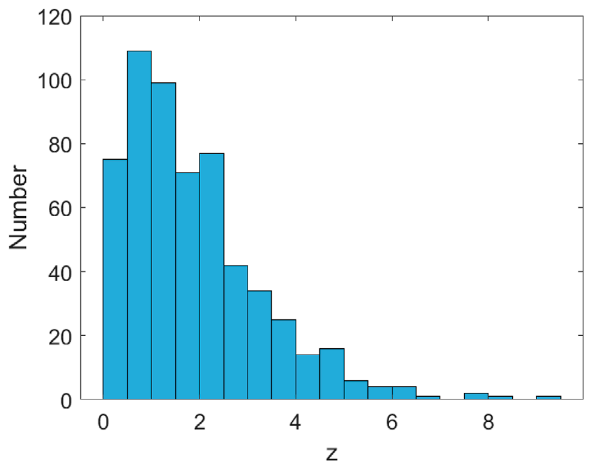

FIGURE 1
The distribution of GRB redshifts.

3.2.4 Machine learning

As long as the host galaxy can be detected, the redshift measurement methods of ordinary galaxies can be applied to the GRB afterglow or host galaxy. Besides template matching method, training set methods are also very common. Training set methods usually use machine learning technology to estimate redshift, which is based on statistical theory. These methods need a training data set, which contains samples of data or images with both spectroscopic and photometric redshifts. Redshift

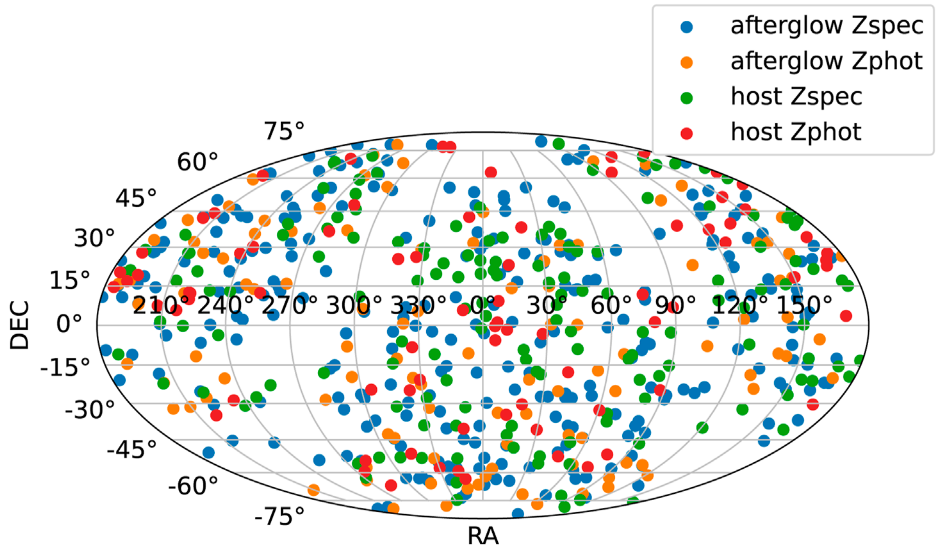

FIGURE 2
Distribution of GRB right ascension (RA) and declination (DEC).

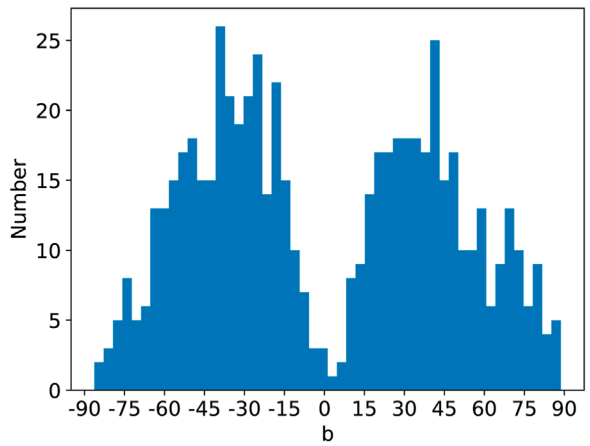

FIGURE 3
The distribution of GRB galactic latitude (b).

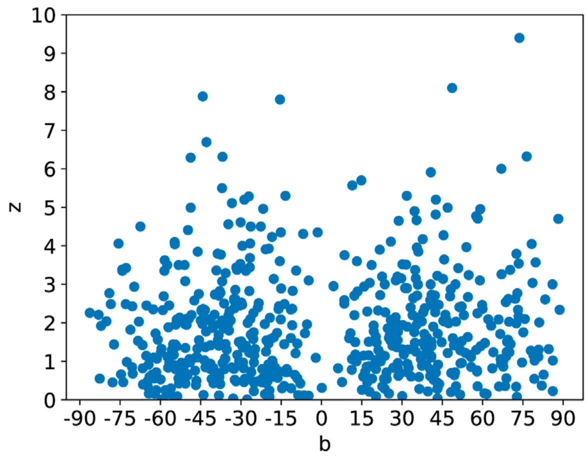

FIGURE 4
Correlation between galactic latitude (b) and redshift (z).

without spectroscopic measurement can be estimated by building a fitting model based on spectrum and photometric data in the training data set. Some typical methods are Polynomial Function Fitting (Connolly et al., 1995), Bayesian model (Benítez, 2000), Support Vector Machine (Wadadekar, 2005), K-Nearest Neighbor (Beck et al., 2016), Kernel Regression (Wang et al., 2008), Random Forest (Carrasco and Brunner, 2013), Active Learning (Han et al., 2015), Artificial Neural Network (Firth et al., 2003) and so on. The latest methods are Ensemble Learning (Cunha and Humphrey, 2022), Deep Capsule Network (Dey et al., 2022) and so on.

Compared to traditional processing methods, machine learning has the advantage of high efficiency. But the sample size of GRB hosts is far smaller than that of the normal galaxies. However, machine learning methods can still be useful in combination with other redshift estimation methods to improve the accuracy and speed of the analysis.

3.3 Pseudo-redshift estimation method

Besides the methods mentioned in section 3.1 and 3.2, pseudo-redshift can also be estimated according to the luminosity-indictor relationships, which contain some GRB observed features such as spectral peak energy, spectral complexity, light variation,

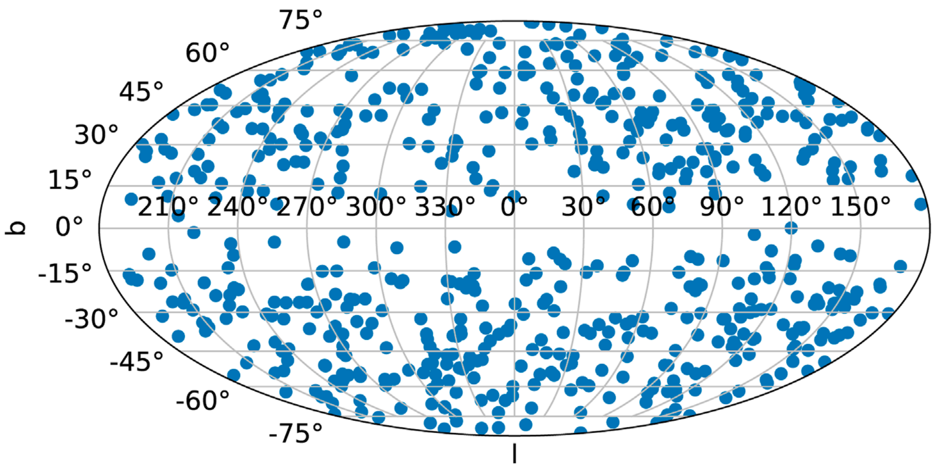

FIGURE 5
Distribution of GRB galactic longitude (l) and galactic latitude (b).

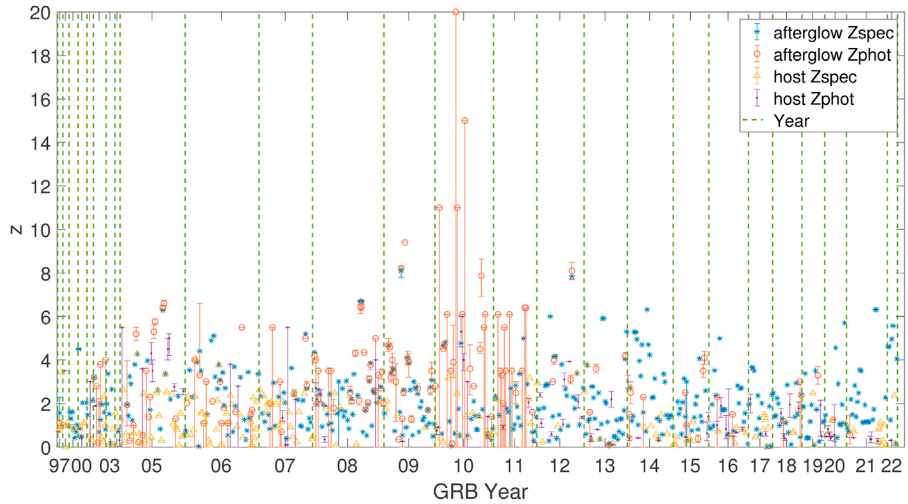

FIGURE 6
Comparison of different measurement methods of redshift. The horizontal axis represents the years of the GRBs, and the vertical axis represents the redshift. GRBs redshifts with known errors are described by error bars. For the GRBs with a certainly range limitation, the bottoms of error bars are connected to the zero-value point.

afterglow correlation, etc (Tan et al., 2013). This redshift estimation method was popularly used in the Compton BATSE era (Lloyd-Ronning et al., 2002). The advantage of this method is that it is completely independent of real redshift measurements in section 3.1 and 3.2, so Pseudo-redshift estimation cannot be affected by redshift selection effects such as redshift desert. Moreover, it can provide a larger amount of redshift data. However, the accuracy of the estimation depends on the tightness of the correlations between the observed features and redshift, and it may not be reliable for all GRBs (Guo, 2020). The method was applied in GRB 080514B ($z = 1.76 \pm 0.30$), and its photometric redshift is $z = 1.8^{+0.4}_{-0.3}$ (Rossi et al., 2008).

4 Statistical characteristics of GRB redshifts measured by different methods

The purpose of this paper is to explore various measurement methods of GRB redshift, so as to help astronomers choose accurate and effective measurement methods and apply them to future exploration. Therefore, in addition to the theoretical study of the algorithm, it is necessary to perform statistics on GRB redshift and show the applicable scope of these measurement methods in practical application.

We collect 611 GRBs with redshifts measured since 1997, as shown in Supplementary Table S2. The afterglow z_{spec} indicates spectroscopic redshift measured by spectral measurement method of afterglow. The afterglow z_{phot} indicates photometric redshift measured by Afterglow SED fitting method. The host z_{spec} indicates measurement by spectral measurement method of host galaxy. The host z_{phot} indicates measurement by template matching method of host galaxy.

581 GRBs have accurately measured redshifts, with a range from 0.0085 to 9.4. 30 GRBs redshift only have an upper or lower limit. Some GRBs have been measured by several methods or the same method several times, and these GRBs have multiple redshift values. In a few cases, afterglow z_{phot} and host z_{phot} may have large differences in several measurements. One example is GRB 191031D. The photometric redshift methods select the redshift with the minimum χ^2. Although, χ^2 values of the afterglow z_{phot} measurement and host z_{phot} measurement may be similar, the redshift values of each result can have large differences.

The distribution of GRB redshifts is shown in Figure 1. The mean value is $\bar{z} = 1.8820$, the median value is $z_{med} = 1.5200$, and the standard deviation value is $s = 1.4148$.

As shown in Figure 2, GRB is randomly distributed on the celestial sphere. When $RA < 180°$, $-90° < DEC < 0°$, there are 151 GRBs; when $RA < 180°$, $0° < DEC < 90°$, there are 160 GRBs; when $RA > 180°$, $-90° < DEC < 0°$, there are 125 GRBs; when $RA > 180°$, $0° < DEC < 90°$, there are 175 GRBs. In addition, afterglow z_{spec}, afterglow z_{phot}, host z_{spec} and host z_{phot} GRBs are also randomly distributed on the celestial sphere respectly.

As shown in Figures 3, 4, GRBs are less distributed in the low galactic latitudes. It is very difficult to find GRBs in galactic disk, due to the serious dust extinction, reddening and dense star field in galactic disk. In the high galactic latitudes, there are few transients such as GRB. There is no obvious correlation between galactic latitude and redshift. GRB with the highest redshift (GRB 090429B) is $b = 73.72°$.

As shown in Figure 5, except for the low galactic latitude, GRB is uniform distributed on the galactic celestial sphere, which proves that GRB is isotropic.

Comparison of different measurement methods of redshift is shown in Figure 6. It can be seen that the redshift distribution measured in different years is similar. While the dark host galaxy and the detection limit of current equipment, it is difficult to detect the host galaxy with high redshift. With the increase of redshift, the errors of all methods are relatively increased. The accuracy of spectral measurement is usually higher than that of photometric measurement. At present, the highest redshift of GRB 090429B belongs to afterglow z_{phot}, as the afterglow is relatively bright. As GRB afterglow is relatively brighter than host. In order to improve the redshift measurement accuracy, we can combine above methods and take all the advantages of the various methods.

5 Summary and prospect

We introduce the research history and scientific significance of GRB redshift. Two types of measurement methods for GRB redshift are mainly summarized. The two types are the measurement methods based on afterglow and the measurement methods based on host galaxy. We have also outlined the principles, methods, and processes involved in GRB redshift measurement, and summarized the applications of different redshift measurement methods. Finally, we summarized and discussed the distribution of 611 GRBs with redshift measured by various methods.

SVOM mission is dedicated to GRB detection especially for high redshifts thanks to its gamma-ray detector payload, ECLAIRs, is more sensitive in softer the energy range of 4–150 keV (Wei et al., 2016). After ECLAIRs is triggered, SVOM can take follow-up observation quickly with its payload telescope Visible-band Telescope (VT), which can detect GRB at $z > 6.5$, and narrow-field ground-based robotic follow-up telescope (F-GFT and C-GFT) in multiple bands. The F-GFT will take broadband optical/infrared photometry with r and J simultaneous bands, operating in 0.4–1.7 μm. While C-GFT has SDSS g, r, i bands to operate photometry in 0.4–0.95 μm (Wei et al., 2016). The two ground telescopes, which have characteristics of high availability, can perform follow-up observations with, good sensitivity, fast pointing speed, low read-out time, high-precision localization and so on. GFTS can measure redshift from ~2.5 to ~6 with its multi-bands photometry if afterglow of GRB is detected. Lyman-α line is beyond the range of GFTs bands at $z < 2.5$, so the redshifts of these GRBs can be obtained by detecting host galaxies rather than afterglows. SVOM will also cooperate with facilities such as James Webb Space Telescope (JWST) and Extremely Large Telescopes to detect the host galaxies. To detect GRBs with high redshift, SVOM can raise optical-counterpart alerts quickly. Alerts can trigger large ground telescopes to observe afterglow and measure the spectroscopic redshift of GRB. In addition, SVOM has the anti-solar pointing strategy, so large telescopes can observe GRBs at early times, which is also helpful for the detection of GRBs with high redshifts (Wei et al., 2016). To sum up, several measurement methods of GRB redshift can be comprehensively applied to SVOM mission. For example, Wang et al. (2020) considered the polynomial fitting method to simulate the relationship between the B-R colors and spectroscopic redshift. We will consider to use machine learning methods to measure redshift in the future.

Author contributions

CL and CW are responsible for the construction of the overall framework of the article. JM is responsible for literature collection, data collection, theoretical guidance and writing guidance. ML is responsible for literature collection, data collection, experiment design, data analysis and writing. ZK is responsible for theoretical and writing guidance. ZL is responsible for literature collection and theoretical guidance. SD and BN are responsible for data collection. PJ is responsible for writing guidance. In addition, All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspas.2023.1124317/full#supplementary-material

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