1. Introduction

Gamma-ray bursts (GRBs) are the most energetic electromagnetic astrophysical phenomena known today. They are typically discovered and classified by their characteristic fast-rising, luminous emission of gamma-ray photons, the so-called prompt emission phase, and they are typically followed by a multi-band emission, known as afterglow. Depending on the time duration, GRBs are classified into short (less than 2 s) and long GRBs, which last ~30 s (Kouveliotou et al. 1993). Recently, short GRBs have been observed to form in association with kilonovae and gravitational wave emission, suggesting that they originate in compact object mergers (e.g., Narayan et al. 1992; Abbott et al. 2017a,b; Makhathini et al. 2021). Long GRBs are theorized to occur after the collapse of a massive star into a black hole (e.g., Woosley 1993), or a magnetar (e.g., Usov 1994), and they are often associated with supernovae (e.g., Hjorth et al. 2003). GRB afterglows are usually attributed to the interaction between an ultra-relativistic jet that is launched during the formation of the compact object, and the circum-burst medium. The observed multiwavelength synchrotron emission is thought to be due to the propagation of two shocks, a forward shock and a reverse shock, with the latter dominating at early times (Piran 1999, 2004). If an ordered magnetic field is present in the ejecta, the reverse shock can be highly polarized (e.g., Granot & Königl 2003). The polarization of the forward shock depends on the morphology and intensity of the circum-burst magnetic field (Uehara et al. 2012).

The exact emission mechanisms, geometry, and physical properties of the emission region in GRBs are currently not well understood. Polarimetric observations of GRBs, both in the prompt phase and during the afterglow, can potentially reveal some of their unknown properties. Polarization in the prompt phase of the GRBs in the γ-ray band is expected to arise due to synchrotron radiation (e.g., Granot & Königl 2003; Waxman 2003; Metzger et al. 2011), inverse Compton (e.g., Shaviv & Dar 1995), or fragmented fireballs (e.g., Lazzati & Begelman 2009), and the expected levels of polarization are in the order of several tens of percent, depending on the model, while observations are in agreement with the predictions (see Covino & Gotz 2016 for a review). However, recent results by Cole et al. (2020) reveal cases where the polarization of the prompt phase in the 50–500 keV energy range can be as low as zero.

There have been several polarimetric measurements of optical GRB afterglows. Most late GRB optical afterglows display polarization degree values of a few percent (Covino & Gotz 2016). However, early-time optical afterglows systematically display higher values of polarization (tens of percent), which has been attributed to ordered magnetic fields within the jets, strong enough not to be distorted by the reverse shock (Deng et al. 2017). Whether magnetic fields around GRBs are mostly ordered or random can have an observable effect on their polarization, which is mostly related to the variations in the polarization angle in time (Teboul & Shaviv 2021).

There are some notable examples of single-epoch optopolarimetric measurements of GRB afterglows. For example, Steele et al. (2009) measured the polarization of the early afterglow of GRB 090102 at 10.1 ± 1.3%. Uehara et al. (2012) presented a polarization measurement of GRB 091208B, 149–706 s after the trigger at the level of 10.4 ± 2.5%.

Time-resolved measurements could provide better insights into the processes following a GRB. For example, Mundell et al. (2013) observed the optopolarimetric evolution of GRB 120308A and reported a polarization degree of 28 ± 4, decreasing to 16±3%, with the polarization angle remaining constant during the observations. Recently, Shrestha et al. (2022a) followed GRB 191016A, 3987–7687 s after the burst and reported evidence of polarization in all phases, with a peak...
of 14.6 ± 7.2%, which coincides with the start of the flattening of the light curve. Shrestha et al. (2022b) present time-resolved optopolarimetric measurements of several GRB afterglows, finding evidence of polarization in two of them, with one of them being GRB 191016A as discussed above.

In this paper we report on the optical afterglow polarization of the long GRB, GRB 210619B, ~5967–8245 s post-burst. On June 19, 2021, at 23:59:25 UT, the Swift Burst Alert Telescope (BAT) triggered and located GRB 210619B (D’Avanzo et al. 2021). The GRB was also detected by GECAM (Zhao et al. 2021), the Konus-Wind experiment (Svinink et al. 2021), and the Fermi Gamma-Ray Burst Monitor (Poolakkil et al. 2021). de Ugarte Postigo et al. (2021) observed the optical afterglow with OSIRIS on the 10.4 m GTC telescope at Roque de los Muchachos Observatory and measured its redshift $z = 1.937$. They also detected an intervening system at $z = 1.095$. Atteia (2021) noted the probability of a lensed visible afterglow in the following months due to this intervening system.

Oganesyan et al. (2021) combined multifilter optical observations together with X-ray and γ-ray data to model the emission of the GRB. They disentangled the contributions of the reverse and forward shocks and argued that the GRB multiwavelength emission is produced by a narrow, highly magnetized jet propagating in a sparse environment, with an approximate jet-break time at $\sim 10^3$ s. A comparison between the optical and X-ray data shows evidence of a secondary component of radiation in the jet wings.

2. Observations and data reduction

2.1. GRB observations

We conducted optical polarimetric observations of the afterglow of GRB 210619B with the RoboPol instrument, which is mounted on the 1.3 m telescope at the Skinakas Observatory in Crete\(^1\). RoboPol is a four-channel polarimeter without rotating parts that can measure the linear Stokes parameters $I$, $q = Q/I$, and $u = U/I$ in a single exposure (Ramaprakash et al. 2019). The instrument splits the incoming light into four beams, corresponding to four orthogonal polarization directions, and it projects four spots on the CCD in a cross shape for each of the imaged sources. It is optimized for a single source placed in the center of the field of view by using a mask in the telescope focal plane, which is designed to significantly lower the background and prevent overlapping between sources. Observations with RoboPol are performed using an automated pipeline (King et al. 2014b). In the case of targets of opportunity, such as GRBs, the automated system informs the observers and provides the coordinates of the event. For example, RoboPol was used to observe the optical afterglow of GRB 131030A, where King et al. (2014a) measured a constant linear polarization value of $p = 2.1 \pm 1.6\%$ throughout the observations.

Following the trigger of GRB 210619B, regular observations were interrupted and the telescope was pointed toward the GRB location. We began taking exposures in the Sloan Digital Sky Survey (SDSS) $r$ band at 1:37:12.00 UT on June 20, 2021, ~5867 s after the trigger (~1998 s after the burst in the source frame). At the time of observations, it was already morning astronomical twilight. Therefore, we observed the GRB afterglow by taking a series of 200-s exposures until the background was too high to allow for more observations. This resulted in 11 200-s exposures. For the first five of them, we were able

\(^1\) https://skinakas.physics.uoc.gr/
of sight of the GRB is 0.12–0.14 mag (depending on the choice of equation for unit conversion between Green et al. 2019 units and $E(B-V)$ – see Green 2018). The upper limit for the polarization induced by dust alignment in the ISM is 13% $\times E(B-V)$ (Panopoulou et al. 2019; Planck Collaboration XII 2020). Based on this estimate, the expected maximum ISM-induced polarization in the line of sight is 1.6–1.8%. However, field stars in the same line of sight have an average polarization value of $P = 0.26 \pm 0.05\%$. This could be due to the presence of multiple dust clouds in the line of sight, which are permeated by magnetic fields with different orientations. This configuration would align dust grains in different directions in each cloud and thus give rise to depolarization of the light of distant stars (e.g., Tassis et al. 2018). The steps seen in the reddening plot in Fig. 1 hint at such a scenario.

Another way to estimate the ISP is by using the polarized thermal emission map provided by Planck Collaboration Int. XIX (2015). Dust grains absorb optical light, which is preferentially polarized parallel to their major axis. Therefore, in the case where dust is ordered (e.g., due to the presence of a magnetic field), light would appear preferentially polarized in the direction perpendicular to the dust grains. The light absorbed by dust is reemitted in the far-infrared, with a polarization along the major axes of the grains. It follows from this that thermal emission is expected to be polarized in the plane perpendicular to the optical polarization produced by the ISM. Planck Collaboration Int. XXI (2015) studied the polarization of 206 stars in the submillimeter and optical ranges and provided the correlation of the Stokes parameters $q = Q/I$ and $u = U/I$ between the two bands. The correlation is clear and robust. Thus, the optical ISP can be directly inferred by the submillimeter measurements of Planck Collaboration Int. XIX (2015) on the same line of sight. We derived the optical ISP using Planck data for the region centered in the location of the GRB with two different resolutions, 30′ and 15′.

We show the measurements of the field stars together with the optical ISP derived by the Planck measurements in Fig. 2. For comparison, we also plotted the weighted mean of the first five GRB measurements on the same plot – not corrected for the ISM contribution (see Sect. 3 for more details). Information on the ISP and mean GRB measurements is presented in Table 1. The weighted mean of the field stars and the ISP value obtained by the Planck 15′ measurement are well consistent with each other. Since we only have three field stars for the ISP estimation, we decided to use the Planck value since the Planck beam averages over a dust column with a larger cross section, which gives a higher signal-to-noise ratio (S/N). The field stars served as an additional confirmation of the validity of Planck data in the line of sight of interest. We favor the 15′ over the 30′ resolution, since it gives information about the ISP on more localized scales and it should better reflect the true value of the ISP in the line of sight of the GRB. Finally, Skalidis & Pelgrims (2019) have shown that using Planck submillimeter polarization data in such a scale to infer the optical ISP is a reasonable choice that provides accurate and high-S/N measurements.

In the case when the object is extragalactic, such as GRBs, the host galaxy ISM could also potentially polarize the observed light. Host-induced polarization is proportional to the amount of dust present around the location of the burst and it can be probed by the reddening of the GRB. In our case, Oganesyan et al. (2021) find that the host galaxy reddening is negligible, and therefore the host-induced polarization should be negligible as well.

The final measurement and uncertainties of Stokes $q = Q/I$ for each of the exposures is simply the following:

$$q = q^\text{measured} - q^\text{instrumental} - q^\text{ISP}$$

(1)

$$\sigma_q = \sqrt{(\sigma_{q^\text{measured}})^2 + (\sigma_{q^\text{instrumental}})^2 + (\sigma_{q^\text{ISP}})^2}$$

(2)

and, similarly for Stokes, $u = U/I$.

Table 1. Polarization of field stars corrected for instrumental polarization and their weighted mean together with the optical ISP derived from Planck using two different resolutions, 30′ and 15′, as well as the weighted mean and errors on the mean of the first five GRB measurements.

| Star ID | RA deg | Dec deg | Dist. kpc | $r$ mag | $Q/I$ % | $U/I$ % |
|---------|--------|---------|-----------|--------|--------|--------|
| Field Star 1 | 319.7258658 | 33.8492013 | 4.3 | 13.85 | 0.34 ± 0.15 | 0.11 ± 0.05 |
| Field Star 2 | 319.7152985 | 33.8603076 | 4.2 | 13.90 | 0.30 ± 0.10 | 0.08 ± 0.16 |
| Field Star 3 | 319.7351566 | 33.8638350 | 3.2 | 15.7 | 0.25 ± 0.06 | 0.12 ± 0.11 |
| Weighted Mean | – | – | – | – | 0.25 ± 0.04 | 0.07 ± 0.13 |
| Planck 30′ | 319.71831 | 33.85044 | – | – | 0.16 ± 0.02 | 0.19 ± 0.02 |
| Planck 15′ | 319.71831 | 33.85044 | – | – | 0.25 ± 0.02 | 0.11 ± 0.02 |
| GRB | 319.71831 | 33.85044 | – | – | 1.50 ± 0.31 | 0.46 ± 0.28 |
Table 2. Measurements of the degree of polarization and EVPA of the GRB.

| Time since GRB (s) | Observer’s frame | Source’s frame | \( P \) | \( P_{\text{debiased}} \) | EVPA | EVPA_{\text{debiased}} |
|-------------------|------------------|----------------|-----|----------------|-----|---------------------|
| 5967              | 2032             | 0.9 ± 0.7      | 0.7 ± 0.7 | 37 ± 21 | 37 ± 29 |
| 6177              | 2103             | 1.6 ± 0.7      | 1.4 ± 0.7 | −6 ± 13 | −6 ± 15 |
| 6537              | 2226             | 2.3 ± 0.7      | 2.2 ± 0.7 | 22 ± 9  | 22 ± 10 |
| 6751              | 2299             | 2.7 ± 0.8      | 2.6 ± 0.8 | 2 ± 8   | 2 ± 8   |
| 6964              | 2371             | 1.7 ± 0.8      | 1.5 ± 0.8 | 14 ± 14 | 14 ± 16 |
| **Average**       |                  | 1.6 ± 0.3      | 1.5 ± 0.3 | 8 ± 5   | 8 ± 6   |

Likely not affected by the background

| Time since GRB (s) | Observer’s frame | Source’s frame | \( P \) | \( P_{\text{debiased}} \) | EVPA | EVPA_{\text{debiased}} |
|-------------------|------------------|----------------|-----|----------------|-----|---------------------|
| 7178              | 2444             | 4.1 ± 0.9      | 4.0 ± 0.9 | −9 ± 7  | −9 ± 7  |
| 7391              | 2517             | 1.1 ± 1.0      | 0.8 ± 1.0 | 5 ± 27  | 5 ± 36  |
| 7604              | 2589             | 2.5 ± 1.1      | 2.3 ± 1.1 | −31 ± 12| −31 ± 14|
| 7818              | 2662             | 3.4 ± 1.5      | 3.1 ± 1.5 | −17 ± 13| −17 ± 15|
| 8031              | 2735             | 5.6 ± 1.7      | 5.3 ± 1.7 | 2 ± 8   | 2 ± 10  |
| 8245              | 2807             | 1.0 ± 2.0      | 0.6 ± 2.0 | −23 ± 56| −23 ± 52|

Notes. Time corresponds to the median time in the observer’s frame of each 200 s exposure.

Fig. 4. Simulation measurements for a source with input polarization \( P = 2\% \). Each panel shows the case of a different input EVPA: 0°, 45°, 90°, and 135°. Top of each panel: measurements of polarization for each of the simulated frames with their 1σ uncertainties. Bottom of each panel: EVPA measurements for each of the simulated frames with their 1σ uncertainties, together with the measured EVPA and 1σ uncertainty of the polarized sky for comparison. We note that the last exposure could not be measured in two out of the four simulations (for input EVPAs of 0 and 45 deg). EVPAs are shown interchangeably either in the (−90,90] or [0,180) range for clarity.

3. Results and discussion

We present the time evolution of the degree of polarization (\( P \)) and the electric vector position angle (EVPA) of our observations in Fig. 3. Since polarization is a nonnegative quantity, measurements are biased toward higher values, especially those with a low S/N (e.g., Vaillancourt 2006). In Table 2, we present both the raw measurements and the debiased values for the polarization. Debiasing was performed according to Plaszczynski et al. (2014). All the provided values in Table 2 and Fig. 3 have been
corrected for instrumental polarization and ISP. Since the observations were made during morning twilight, we considered the possibility that the rise in the background affected our measurements (the morning sky is highly polarized). The stars in the RoboPol field cannot be confidently measured to compare how their polarization changes with time, allowing us to investigate this scenario. For this reason, we ran simulations as follows: We made four fake images for each of our exposures by replacing the GRB source in our images with a mock source with polarization $P = 2\%$, and a different value of EVPA for each of the four images, $0, 45, 90,$ and $135^\circ$. The full-with half-maximum (FWHM) and intensity of the source in each frame matched the FWHM and intensity of the corresponding real exposure. Then, for each of the fake frames, we conducted the analysis in the same way as for the real observations. We present the output of the simulations in Fig. 4. It becomes obvious that the latter observations in all cases tend to be farther away from the real values than from the former. Especially in the simulations with input $\text{EVPA} = 0^\circ$ (top left of Fig. 4), the measurements of EVPA tend to drift toward the background value. A similar drift seems to be apparent in the last measurements of the simulation with input $\text{EVPA} = 45^\circ$ (top right of Fig. 4). Finally, the latter polarization values of all simulations seem to be less accurate, on average, than the first ones. Based on the above, we conclude that the first five measurements are likely the only ones not affected by the polarized sky since they are the only ones that are not affected by the background in all simulations. In this paper, we present all of our measurements, yet we highlight that the last six measurements of the time series are probably seriously affected by the high background. Although RoboPol allows for background estimation for each of the four spots of the source to account for occasions when the background is polarized, in these particular images, the source is fairly faint, the background high, and the sky is highly polarized (~40%). Therefore, a minor deviation of the background estimate from its true value is enough to give rise to the observed behavior. We note that for the first five measurements of the simulation, the scatter in the measured values in the simulations is similar to the one in the observations. Therefore, we postulate that the polarization and EVPA of the GRB are likely constant throughout these measurements. By combining them, we get the debiased values $P = 1.5 \pm 0.3$, $\text{EVPA} = 8 \pm 6^\circ$.

Unlike the previous GRB observed with RoboPol at Skinakas (King et al. 2014a), where the polarization of GRB 131030A was found to be consistent with the interstellar polarization, we get a high-confidence ($5\sigma$) detection of intrinsic GRB afterglow polarization. The degree of polarization measured in this work for GRB 210619B is rather typical for optical GRB afterglows in such scales (e.g., Covino & Gotz 2016). According to the modeling of Oganesyan et al. (2021), at the time of our observations, the optical emission was dominated by the contribution of the forward shock. This level of linear polarization agrees with the long-thought idea that it arises primarily from synchrotron radiation. There are several different models that agree with this level of polarization. However, observations of temporal evolution of GRB polarization over a longer time period are more appropriate to put constraints and test the theory (see Gill et al. 2021 for a recent review).

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