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Optical polarization observations with the MASTER robotic net

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HIGHLIGHTS

- For GRB100906A, GRB110422A, GRB121011A the dimensionless Stokes parameter is obtained.
- The polarization of SN 2012bh at the early stage of the envelope expansion was <3%.
- Polarization measurements for the blazars OC 457, 3C 454.3 are presented.
- Polarization degree for the blazars QSOB1215+303, 87GB 165943.2+395846 are presented.
- MASTER telescopes can safely register linear polarization in excess of 10%.

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ABSTRACT

We present results of optical polarization observations performed with the MASTER robotic net (Lipunov et al., 2004, 2010; Kornilov et al., 2012) for three types of objects: gamma-ray bursts, supernovae, and blazars. For the Swift gamma-ray bursts GRB100906A, GRB110422A, GRB121011A, polarization observations were obtained during very early stages of optical emission. For GRB100906A it was the first prompt optical polarization observation in the world. Photometry in polarizers is presented for Type Ia Supernova 2012bh during 20 days, starting on March 27, 2012. We find that the linear polarization of SN 2012bh at the early stage of the envelope expansion was less than 3%. Polarization measurements for the blazars OC 457, 3C 454.3, QSO B1215+303, 87GB 165943.2+395846 at single nights are presented. We infer the degree of the linear polarization and polarization angle. The blazars OC 457 and 3C 454.3 were observed during their periods of activity. The results show that MASTER is able to measure substantially polarized light; at the same time it is not suitable for determining weak polarization (less than 5%) of dim objects (fainter than 16^m). Polarimetric observations of the optical emission from gamma-ray bursts and supernovae are necessary to investigate the nature of these transient objects.

1. Introduction

Polarimetry plays an important role in modern astrophysics. Polarization measurements provide information about the nature of radiation sources, geometrical properties of the emitting regions, the spatial distribution of matter around sources, magnetic fields.

In the last two decades, the polarimetry, especially spectropolarimetry, has advanced a lot. Different polarization techniques and devices have been developed. Fast CCD cameras and new polarizing materials made polarimetric observations possible for

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a rising number of optical telescopes. In particular, polarization measurements are important for short-living or fast variable objects such as gamma-ray bursts (GRBs) and supernovae.

The first polarization measurements of GRBs afterglow were realized by large telescopes: the 8.2-m Unit Telescopes of VLT (Covino et al., 1999; Rol et al., 2000; Covino et al., 2002), the 10-m Keck I telescope (Barth et al., 2003), the 6.5-m Multiple Mirror Telescope (Bersier et al., 2003). It's remarkable that the first detections of the early optical polarization were performed by a robotic telescope: the 2-m robotic Liverpool telescope (Mundell et al., 2003; Steele et al., 2009). There are also several telescopes with average-size aperture that measure GRBs polarization: the 2.56-m Nordic Optical Telescope (Rol et al., 2003; Greiner et al., 2003), the 2.2-m telescope of Calar Alto Observatory (Greiner et al., 2003), the Kanata 1.5-m telescope at Higashi-Hiroshima Observatory (Uehara et al., 2012), and the 1-m USNO telescope in Flagstaff (Greiner et al., 2003).

The early attempts to measure polarization of Type Ia supernovae were made by using the 2.6-m Shain reflector built for the Crimean Astrophysical Observatory (Shakhovskoi, 1976). The first spectropolarimetric data were obtained on the 3.9-m Anglo-Australian Telescope (McCall et al., 1984). The program of polarimetric observations of SN Ia was begun on the 2.1-m Struve Telescope at McDonald Observatory (Wang et al., 1996; Howell et al., 2001). This program was continued on the 8.2-m unit telescopes of the VLT (Wang et al., 2007). Spectropolarimetry is also carried out on the Keck I 10-m telescope (Chornock et al., 2006).

The first MASTER telescope was mounted in 2002 near Moscow. The MASTER net began operating in full mode in 2010 (Lipunov et al., 2004; Lipunov et al., 2010; Kornilov et al., 2012; Gorbovskoy et al., 2013). More than 100 alert pointings at GRBs were made by MASTER. The MASTER net holds the first place in the world in terms of the total number of first pointings, and currently more than a half of first pointings at GRBs by ground telescopes are made by the MASTER net. More than 400 optical transients have been discovered, among them cataclysmic variables, supernovae, blazars, potentially hazardous asteroids, transients of unknown nature. Photometry of 387 supernovae has been carried out. Polarization measurements is one of the purposes for us to design and construct the MASTER II robotic telescopes. The linear polarization measurements with the MASTER net involve simultaneous observations of an object by several telescopes equipped with cross linear polarizers. Since each telescope of the net has two wide-FOV astronomical tubes, we have to point at least two telescopes[1] to an object simultaneously in order to determine its Stokes parameters.

The unique design of MASTER II makes it the only wide-FOV fully robotic instrument in the world able to measure polarization. In this work we report the results of the examination of its accuracy and analyze its capability to measure polarization of different types of astrophysical objects: gamma-ray bursts, supernova, blazars.

2. MASTER instruments and reduction of observations

Each MASTER II telescope contains a two-tube aperture system with a total field of view of 8 square degrees, equipped with a 4000 pixel × 4000 pixel CCD camera with a scale of $1.85''$/pixel, an identical photometer with B, V, R, and I filters representing the Johnson–Cousins system, and polarizing filters. Both optical tubes are installed on a high-speed mount with position feedback, which does not require additional guide instruments for exposures not exceeding three to ten minutes. The setup has an additional degree of freedom: the variable angle between the optical axes of the two tubes. This allows us to double the field of view during survey observations if the tubes are deflected from each other, or to conduct synchronous multi-color photometry with parallel tubes. A single telescope of the MASTER II net provides a survey speed of 128 square degrees per hour with a limiting magnitude of 20^m on dark moonless nights.

Astrometric and photometric calibration is made by a common method for all MASTER observatories (Gorbovskoy et al., 2013; Kornilov et al., 2012). Bias and dark subtraction, flat field correction, and astrometry processing are made automatically. Bias and dark images obtained before the beginning of observations and the closest in time flat field images, obtained on the twilight sky, are used. To convert magnitudes into absolute fluxes, zero points of the MASTER bands should be used. They can be found at http://master.sai.msu.ru/calibration/.

The first MASTER polarizers were high contrast Linear Polarizing Films combined with usual glass (in January–July 2011 they were combined with R filter instead). Since July 2011 all polarizers have been replaced by new broadband polarizers manufactured using linear conducting nanostructure technology (Kornilov et al., 2012; Ahn et al., 2005). Magnitudes obtained from broadband photometry correspond to $0.2B + 0.8R$ where B, R are the standard Johnson filters (Gorbovskoy et al., 2013). Each tube is equipped with one polarizer, the polarization directions of two tubes in a single assembly being perpendicular to one another. Polarizers' axes are set in two ways with respect to celestial sphere: in the MASTER Kislovodsk and the MASTER Tunka sites, the axes are directed at positional angle 0° and 90° to the celestial equator (polarizers oriented at 45° and 135° were added in Kislovodsk in April 2012), in the MASTER Blagoveshchensk and the MASTER Ural, at angles 45° and 135°. Thereby, using several MASTER telescopes one can realize observations with different orientation of the polarizers. Such a construction is very effective for fast events with significant intrinsic polarization. These events are mostly of extragalactic origin. In spite of the fact that all MASTER telescopes have a similar construction, optical scheme, and polarizers, there are some uncertainties in the channels responses. These limit the precision of polarization measurements. Also, the calibration using known polarized galactic sources is not possible, as any measurement of polarization involves subtraction of nearby field stars between at least three images, obtained with tubes with differently oriented polarizers. Thus the derived polarization of a target object is always relative to the nearby field stars. They are usually chosen from the area around the target source in a radius of $10'$ and bound to have the same polarization due to the similar interstellar matter properties toward them. The original stellar radiation is not polarized, polarization appears when light passes through the interstellar dust. Interstellar polarization can reach high values and strongly depends on the galactic direction and wavelength (Voshchinnikov, 2012).

The goals of the MASTER polarimetric analysis, when observing highly-polarized extragalactic events, are: to (1) find polarization of an event in excess of the average polarization of galactic stars in that direction, (2) remove additional systematic polarization introduced by the instruments, (3) estimate the uncertainty of polarimetric measurements by MASTER.

Stars with zero polarization are required for the channel calibration. We assume the polarization of light from stars in the field of view is small. This can be checked using Serkowski law (Serkowski et al., 1975). The difference in magnitudes between two polarizers orientations averaged for all reference stars gives the correction that takes into account different channel responses.

3. GRB polarization observations

Gamma-ray bursts are the most powerful explosions in the Universe. Unfortunately, the physics of the process is not fully

[1] The photometer in Kislovodsk contains 4 differently oriented polarizers, which allows us to measure linear polarization at this site alone.

understood. In particular, this is due to the fact that GRBs are short-living events. The spectral investigations argue for synchrotron nature of the GRB emission. It is known that the synchrotron emission in ordered magnetic field is polarized. Thus, observable polarization depends on the degree of coherence of magnetic fields and on the geometrical properties of the emitting regions. Theoretical models with ordered magnetic field predict polarization about 20–30% (Granot, 2003). It is a challenge to test this prediction since GRB are fast variable objects with characteristic times about tens of seconds.

We formally divide optical observations of GRBs into three types: afterglows, early-time, and prompt, in succession of time elapsed from the gamma trigger. Historically, the optical observations of GRBs progressed from afterglows to prompt.

To date, there are no robust positive observations of GRB prompt emission polarization, and only several measurements of afterglow polarization, generally on a level of about 1–3%. These are GRB990510 that showed $(1.7 \pm 0.2)\%$ polarization at around $980T_{90}$ (Covino et al., 1999), GRB020813, with detected polarization varying from 2% $(670 - 1140T_{90})$ to 0.8% $(3300 - 3570T_{90})$ (Barth et al., 2003; Covino et al., 2002), GRB021004 with ~ 1–2% at $t > 500T_{90}$ (Lazzati et al., 2003) and GRB030329 with 0.3–2.5% $(t > 1700T_{90})$ (Greiner et al., 2003).[2] An exception is GRB020405 for which a highly significant polarization $(9.9 \pm 1.3)\%$ (1.3 days after the GRB) was detected (Bersier et al., 2003). However this result is not confirmed by measurements of other teams, which obtained $(1.5 \pm 0.4)\%$ (1.2 days after the GRB) (Masetti et al., 2003); $(1.96 \pm 0.33)\%$ and $(1.47 \pm 0.43)\%$ (2.2 and 3.25 days after the GRB) (Covino et al., 2003).

For afterglow times, we can probe the physics of a relativistic forward shock expanding into surrounding media. Characteristic times can help to distinguish the nature of polarization variability as intrinsic or interstellar (see Covino et al., 2004). Dust destruction in the vicinity of a gamma-ray burst due to the strong radiation field (Waxman and Draine, 2000; Perna and Lazzati, 2002) would result in a monotonically decreasing polarization degree with a constant position angle (Greiner et al., 2003). For such low levels of polarization, the analysis is difficult, and distinguishing the intrinsic polarization from the polarization in the ISM of Milky Way and host galaxy is model-dependent.

Thus, much effort was put to manage early-time observations, when polarization of the GRB-emission itself is anticipated to be more pronounced. The origin of early optical radiation is also considered alternatively: it can be from the starting forward shock or from the reverse shock (Sari et al., 1998; Sari and Piran, 1999; Kobayashi, 2000). In the latter case, polarization is expected to manifest the structure of intrinsic magnetic filed more directly.

At the front of the forward shock, patches of coherent magnetic filed may be generated stochastically. A theoretical model by Gruzinov and Waxman (1999) suggests 10% polarization as an upper level with erratic variations of the position angle. Specific patterns of polarization evolution are predicted in the models concerning beamed synchrotron radiation from a jet observed out of its symmetry axis, even if magnetic fields are completely tangled (see references in the review by Covino et al. (2004)). So far, unfortunately, predicted patterns are not seen clearly in observations, implicating that the presumed jet models are far too simple.

Few early observations of optical polarization exist. For GRB060218, Mundell et al. (2003) reported an upper limit of 8% for times corresponding to the onset of the forward shock, basing on a 30 s-exposure observation started at $2T_{90}$. GRB090102 (Steele et al., 2009) manifested 10% polarization in the early optical emission (a single 60 s exposure started at $6T_{90}$), with emission interpreted as an emission from a reverse shock. Both polarization measurements were performed with a rotating polarizer of the 2.0-m Liverpool robotic telescope. GRB091208B (Uehara et al., 2012) revealed 10% in optical emission, interpreted as an early afterglow (forward-shock emission) obtained on the Hagashi-Hiroshima 1.5 m telescope, measured for an interval $10 - 50T_{90}$.

The prompt observations, simultaneous with the gamma signal, may shed light on another physics, more directly connected with the GRB engine – the structure of the magnetic field within the original outflow. Prompt GRB emission is thought to originate from the jet material interacting with itself. The magnetic fields can be advected from a central engine. If the fireball is electromagnetically dominated, during the first ten minutes the degree of polarization may be >40% (Lazzati, 2006).

For the prompt GRB emission, so far only observations in gamma diapason delivered polarization results: first, GRB021206 was claimed to have 80% polarized prompt gamma-emission but this was critisized later (see Covino et al., 2004). Later, several GRBs are reported with linear polarization of gamma prompt emission at levels 20–80%: GRB041219 (Götz, 2009), GRB100826A (Yonetoku et al., 2011), and, recently, GRB110301A and GRB110721A (Yonetoku et al., 2012).

We would like to stress that especially in cases when optical flash is observed simultaneously with the gamma-ray emission, detection of the polarization of the GRBs optical counterparts is a crucial component to our understanding of the jet physics. If it is produced by a reverse shock, intrinsic magnetic fields can be tested.

The MASTER net was designed with the objective to deliver polarization information as early as possible after GRB triggers. More than 100 observations of GRB were made by the MASTER global robotic net. Optical emission was detected for 11 GRBs. GRB100906A, GRB110422A and GRB121011A deserved attention because their optical observations were carried out during the gamma-ray emission. Regarding the three GRBs considered below, the optical polarization observations were made by MASTER only in two polarizers, and no significant difference was found in two channels for each of them. Unfortunately, it is impossible to make a conclusion about the absence of polarization if you have observations only in two polarizers (there is a possibility that the polarization plane lies at 45 degrees to the polarizers). Electromagnetic radiation can be described in terms of the Stokes vector, which consists of 4 components: I (total intensity); Q, U (describe linear polarization); V (describes circular polarization). The degree of linear polarization P and polarization angle θ can be expressed in terms of the Stokes parameters as $P = \frac{\sqrt{Q^2+U^2}}{I}, \theta = \frac{1}{2} arctan \frac{U}{Q}$. Single dimensionless Stokes parameter is the lower limit of the degree of linear polarization, that is, the actual P can be positive even if one Stokes parameter $\left(\frac{I_1 - I_2}{I_1 + I_2}\right)$ is zero with some uncertainty. The problem of probabilistic estimates of the degree of linear polarization from observations with two polarizers was addressed in the Appendix of Gorbovskoy et al. (2012a).

3.1. GRB100906A

The Tunka MASTER II telescope pointed at the object 23 s after receiving the alert signal (38 s after the registration of the burst by the Swift space observatory (Evans and Marshall, 2010)). The object of 13^m was detected. A series of frames using polarizers with exposures growing from 10 to 180 s were obtained over the next four hours (see Table 4 of Gorbovskoy et al. (2012a)). The duration of the GRB in the gamma-rays was $T_{90} = (114 \pm 1.6)$ s (Markwardt et al., 2010). Thus, the first three frames of the series were obtained simultaneously with the GRB. For the first three minutes, the GRB was synchronously observed in optical, X-ray $(0.3 - 10\ \mathrm{keV})$, and

[2] Here, T_{90} is the standard characteristic time for GRB duration, whose values can be found in the papers cited above.

gamma diapason (15 − 150 keV). Note that it was the first optical polarization observations of prompt GRB emission. The absolute photometry in MASTER wide band is presented in Fig. 1.

The differences in signals obtained in each polarization in the time interval from 100 to 10^4 s were computed $\left(\frac{I_1-I_2}{I_1+I_2}\right)$. It was found that this difference is smaller than the standard deviation of $\frac{I_1-I_2}{I_1+I_2}$ for field stars, which is equal to 2%.

3.2. GRB110422A

The Tunka MASTER telescope was the first ground-based telescope to point at GRB110422A (Mangano et al., 2011), 53 s after beginning of the burst and 37 s after receiving the alert. The observations were carried out in both tubes in mutually perpendicular polarizations. The exposures were successively increased from 10 to 180 s. An optical transient was detected in the very first 10-s frame. The observations were disrupted 35 min after they started because of bad weather conditions. 30 exposures were obtained, 15 in each polarization (see Fig. 2 and Table 1) (Gress et al., 2011a; Gress et al., 2011b).

In spite of the fact that the GRB formally ended before the first MASTER image (the GRB duration was $T_{90}^{BAT} = (25.9 \pm 0.6)$ s (Swift/BAT, Palmer et al., 2011), $T_{90}^{KW} \sim 40$ s (Konus/WIND, Golenetskii et al., 2011), the burst exceeded the 3σ level up to 115 s in the Swift Burst Analyser data (Evans et al., 2009). At least two MASTER observations were made during this interval. Thus MASTER detected prompt emission at those times. The GRB redshift, z = 1.77, was independently determined by different groups (Malesani et al., 2011; de Ugarte Postigo et al., 2011). The dimensionless Stokes parameter does not exceed that of field stars and is less than 2%.

3.3. GRB121011A

GRB121011A (Racusin et al., 2012; Ohno et al., 2012; Xiong et al., 2012) was observed by the MASTER telescopes at two sites (Yurkov et al., 2012; Gorbovskoy et al., 2012b; Lipunov, 2012). The robotic telescope located in Blagoveshchensk was pointed to GRB121011A 51 s after trigger time $T0$ in two polarizations. The Tunka MASTER II robotic telescope (near Baykal lake) was pointed to GRB121011A 106 s after $T0$, also in two polarizations. Thus, the observations began in four polarizations. Unfortunately, the weather conditions turned out poor at Tunka site. The first individual image, on which the optical counterpart was found with Tunka telescope, was taken 230 s after $T0$. About 35 min of optical observations were obtained with the Blagoveshchensk telescope of the MASTER net. The light curve is shown in Fig. 3 and photometry is presented in Table 2.

For interval 0.1-1 h after $T0$, we obtain a zero time-averaged Stokes parameter: $\frac{I_1-I_2}{I_1+I_2} = (1 \pm 2)\%$. For the derived uncertainty of 2%, $1-\sigma$ upper limit for the degree of linear polarization P is about 15% (see Fig. 14 of Gorbovskoy et al. (2012): value of $P = 15\%$ matches $1-\sigma$ probability $\mathcal{L} = 100 - 68\% = 32\%$ for the curve corresponding to a relative accuracy 2%). Another characteristic value is the standard dispersion of Stokes parameters of field stars. It describes the ultimate accuracy of determination of the Stokes parameter for the specific line of sight in the sky at the time. We obtain 6% as the characteristic value of this dispersion for observations of GRB 1210011A.

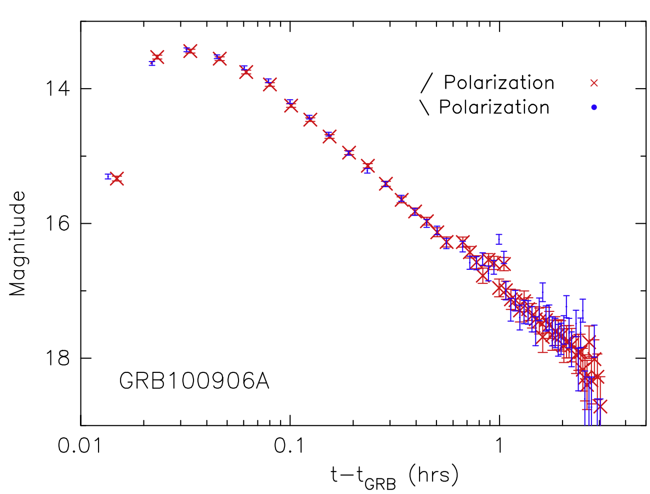

Fig. 1. Light curve of GRB100906A in mutually perpendicular polarizers obtained with MASTER Tunka (Gorbovskoy et al., 2013).

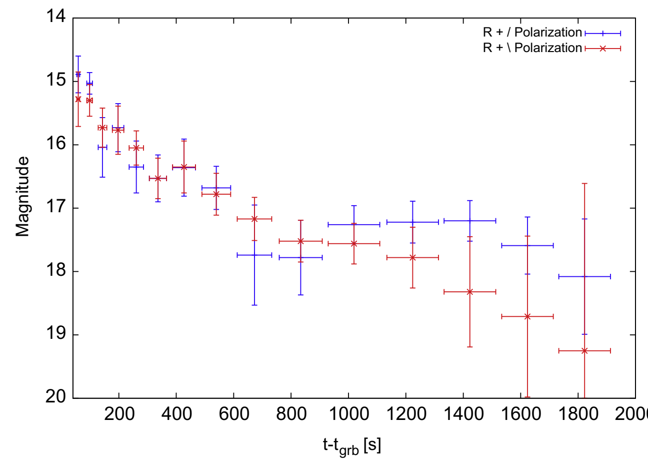

Fig. 2. Light curve of GRB110422A in mutually perpendicular polarizers and R filter obtained with MASTER Tunka (Gorbovskoy et al., 2013).

4. Supernovae polarization observations

As precise standardizable candles, Type Ia supernovae have been used to trace the expansion of the Universe as a function of redshift, leading to the discovery of the accelerated expansion (Perlmutter et al., 1999; Riess et al., 1998). However, several questions related to the physics of the explosion mechanisms are still not well understood. It is generally believed that there are two main mechanisms of Type Ia supernovae explosions: the merger of two white dwarfs (Iben and Tutukov, 1984; Webbink, 1984) and the Schatzman mechanism, according to which a burst is a result of matter accretion on a white dwarf from the companion star in binary systems (Whelan and Iben, 1973). In the first case, which is more often realized in elliptical galaxies (Lipunov et al., 2011), the specific angular momentum of matter is higher than in the second case. This could lead to an anisotropy of the explosion and asymmetrical loss of envelope and, consequently, a significant polarization of optical radiation is expected. Thereby, the registration of significant (more than 2%) polarization can be an independent argument for a model of merging white dwarfs. It should be noted that the continuum polarization depends on the geometry of the explosion but line polarization associates with distribution of matter around supernovae (Wang and Wheeler, 2008).

Previous observations of Type Ia supernovae display close to zero continuum polarization and modest line polarization ∼ 1%. Even if continuum polarization is observed, its value is small: for example, the continuum polarization for SN 1999by (prototype of

Table 1
Optical observations of GRB110422A in mutually perpendicular polarizers and R filter in MASTER Tunka (Gorbovskoy et al., 2013). The absolute fluxes can be obtained using zero-points from http://master.sai.msu.ru/calibration/.

$T - T0$ (s)	R + P\ (mag)	Err (R + P\) (mag)	R + P/ (mag)	Err (R + P/) (mag)
58.5	15.28	0.43	14.89	0.29
98.1	15.3	0.25	15.03	0.17
143.0	15.73	0.31	16.04	0.47
197.3	15.77	0.38	15.73	0.38
261.0	16.05	0.27	16.35	0.41
336.4	16.53	0.32	16.53	0.37
427.1	16.35	0.41	16.36	0.45
539.4	16.78	0.33	16.68	0.34
672.5	17.17	0.34	17.74	0.79
833.7	17.52	0.33	17.78	0.59
1019.3	17.56	0.32	17.26	0.3
1223.8	17.78	0.48	17.22	0.33
1423.0	18.32	0.87	17.2	0.32
1623.7	18.71	1.27	17.59	0.45
1822.8	19.25	2.64	18.08	0.91

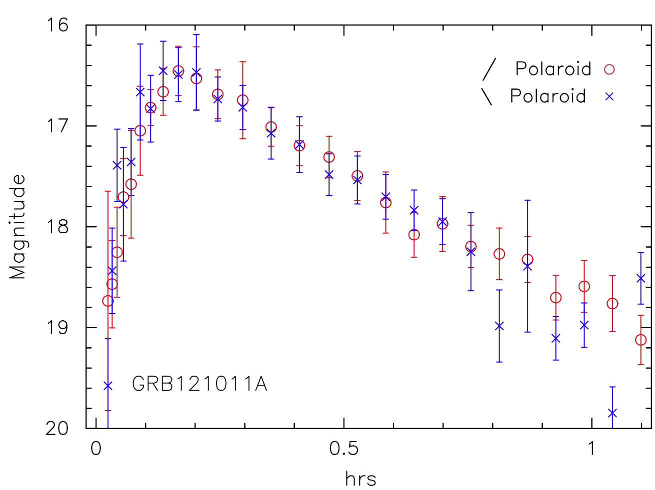

Fig. 3. Light curve of GRB121011A in mutually perpendicular polarizers obtained with MASTER Blagoveshchensk.

which is SN 1991bg) was 0.3–0.8% (Howell et al., 2001), for SN 2005hk $\sim 0.4\%$ (Chornock et al., 2006).

SN 1996X was the first SN Ia with spectropolarimetry prior to the optical maximum. The broadband polarimetry showed that continuum polarization is zero. The spectropolarimetry demonstrated spectral features with a rather low polarization $\sim 0.3\%$ (Wang et al., 1997).

It's very important to measure polarization before optical maximum while an envelope is not expanded essentially. Polarization at the latest phase of any supernova is low. For example, Leonard et al. (2005) report spectropolarimetric observations of SN 1997dt 21 days after optical maximum. Polarization was not detected but inessential line polarization in FeII and SiII was found. Another example is SN 2001el (Wang et al., 2003). Before optical maximum the linear polarization in the continuum was ~ 0.2–0.3%. During the next 10 days the degree of continuum and line polarization decreased and disappeared entirely ~19 days after the optical maximum. Spectropolarimetry of SN 2004S 9 days after the maximum light displayed very low polarization (Chornock and Filippenko, 2008). The absence of polarization in the later stages stresses the importance of early polarimetric observations.

Significant line polarization was found for SN 2004dt, for which there were data approximately 7 days before (Wang et al., 2006) and 4 days after the maximum light (Leonard et al., 2005). During this period the polarization of the SiII line varied within the range $\sim 2\%$. Measurements of polarization of the SN 2002bf at approximately the similar time interval as for the SN 2004dt showed CaII line polarization $\sim 2\%$ (Leonard et al., 2005). SN 1997bp and SN 2002bo also showed 1–2% line polarization (Wang et al., 2006).

Interstellar polarization (ISP) in our Galaxy or in host galaxies of supernovae complicates determination of intrinsic supernova polarization. ISP can be estimated using the empirical Serkowski law (Serkowski, 1973). This law was obtained based on observations in our Galaxy, thus we cannot be certain that distribution and structure of dust in host galaxies of supernovae are the same. Host-galaxy ISP can be high enough. For example, in SN 2006X polarization uncorrected for ISP declines from 8% at 4000 Å to $\sim 2\%$ at 8000 Å (Patat et al., 2009). Taking into account ISP these authors obtain polarization of the CaII IR line $\sim 1.5\%$ and the SiII line $\sim 0.5\%$ (10 days before the maximum light).

The number of Type Ia supernovae detected before maximum light is small but a number of those, for which spectropolarimetric or/and polarimetric data were obtained, is much less. SN 2012bh is a good example of a Type Ia supernova that was discovered before maximum light. SN 2012bh, exploded in the Sb galaxy UGC 7228, was first detected by the Pan-STARRS1 Medium Deep Survey on 2012 March 11.50 UT (Chornock et al., 2012a; Chornock et al., 2012b; Gal-Yam et al., 2012). The coordinates of the supernova are $R.A. = 12^h13^m37^s.309$, $Decl. = +46°29'00''.48$ (J2000.0). The object was discovered with an approximate brightness of $z_{P1} = 22.8(AB)$ mag and brightened to $i_{P1} = 16.99$ mag by 2012 March 21.47 UT (Chornock et al., 2012a). The spectrum in the range 480–940 nm obtained on March 15 with the Grand Telescope Canaries identified the object as a young normal SN Ia. Another spectrum in the range 350–740 nm was obtained on March 23 with the 1.5-m telescope at the Fred L. Whipple Observatory on Mount Hopkins, Arizona. Joint processing of these two spectra showed that supernova was detected three weeks prior to the maximum light.

The observations of SN 2012bh were made by the MASTER robotic net in Tunka, Kislovodsk, and Blagoveshchensk in polarizers. MASTER observed the supernova before and after the maximum light, from March 27 to April 15. The image of the supernova obtained by MASTER Tunka is presented in Fig. 4.

The photometry is made in the IRAF/apphot (Tody et al., 1993). From the SDSS-DR7 catalog (Abazajian et al., 2009) 43 comparison stars were selected with the help of application Aladin (Bonnarel et al., 2000). All these stars are less than 10′ from the supernova and brighter than 18 mag. The nearest galaxy is far enough (40′ or 22 pixels) and does not affect an accuracy of the photometry. The robust "centroid" algorithm is used for the background value calculation. The algorithm allows one to exclude the influence of the nearby objects. The data are corrected for the fluctuations of atmospheric opacity using the "Astrokit" program[3] that implements a slightly modified algorithm described in Everett and Howell (2001). This program conducts differential photometry using an ensemble of stars that are close to an object.

In Table 3, photometry results are presented. Images with signal/noise more than 30 are summed up for every night. The combined light curve is presented in Fig. 5. For comparison, the light curve of a "normal" Type Ia SN 1994D is shown. The light curve of SN 1994D is obtained from its light curves in B and R bands (Blinnikov et al., 2006) using relation $0.2B + 0.8R$. Assuming that SN 2012bh is a "normal" Type Ia supernova, its light curve can be approximated by the light curve of SN 1994D with parameters: $T_{max} = 2456017.865$ (March 31), $m_{max} = 15.75$.

[3] developed by V.V. Krushinsky and A.Yu.Burdanov (President Yeltsin Ural Federal University).

Table 2
Optical observations of GRB121011A in mutually perpendicular polarizers in MASTER Blagoveshchensk. The absolute fluxes can be obtained using zero-points from http://master.sai.msu.ru/calibration/.

$T - T0$ (h)	Exposure (s)	P\ (mag)	Err(P\) (mag)	P/ (mag)	Err(P/) (mag)
0.0240	10	19.6	0.5	18.7	1.1
0.0326	10	18.4	0.4	18.6	0.4
0.0426	10	17.4	0.4	18.3	0.4
0.0553	10	17.8	0.6	17.7	0.4
0.0708	10	17.4	0.3	17.6	0.5
0.0892	10	16.7	0.5	17.0	0.4
0.1102	10	16.8	0.3	16.8	0.2
0.1354	10	16.5	0.3	16.7	0.2
0.1662	10	16.5	0.3	16.5	0.2
0.2024	10	16.5	0.4	16.5	0.3
0.2457	10	16.7	0.2	16.7	0.2
0.2959	10	16.8	0.2	16.7	0.4
0.3531	10	17.1	0.3	17.0	0.2
0.4103	10	17.2	0.3	17.2	0.2
0.4701	10	17.5	0.2	17.3	0.2
0.5272	10	17.5	0.2	17.5	0.2
0.5843	10	17.7	0.2	17.8	0.3
0.6416	10	17.8	0.2	18.1	0.2
0.6987	10	17.9	0.2	18.0	0.3
0.7560	10	18.2	0.4	18.2	0.2
0.8133	10	19.0	0.4	18.3	0.3
0.8703	10	18.4	0.7	18.3	0.2
0.9273	10	19.1	0.2	18.7	0.2
0.9845	10	19.0	0.2	18.6	0.3
1.0416	10	19.8	0.3	18.8	0.3
1.0989	10	18.5	0.3	19.1	0.2
1.1562	20	19.0	0.3	18.4	0.4
1.2134	20	18.2	0.3	19.0	0.1
1.2706	20	19.5	0.3	18.8	0.3
1.3277	20	19.7	0.2	19.2	0.2
1.3848	20	18.7	0.3	18.5	0.2
1.4421	20	21.4	0.5	19.5	0.3
1.4996	20	19.2	0.3	19.4	0.3
1.5566	20	19.3	0.3	19.1	0.2
1.6139	20	19.5	0.7	20.2	0.3
1.6711	20	18.9	0.3	19.1	0.3
1.7854	20	21.2	0.3	19.0	0.2
1.9324	20	18.9	0.3	21.6	0.4
2.0145	20	19.8	0.4	20.5	0.3
2.0717	20	21.1	0.3	19.9	0.3
2.1289	20	20.9	0.2	19.6	0.3
2.1861	20	20.5	0.3	21.9	0.3
2.2434	20	19.6	0.5	23.5	0.3
2.3008	20	21.0	0.6	19.9	0.3
2.4152	20	19.7	0.3	19.7	0.3
2.4725	20	18.8	0.4	19.3	0.2
2.5296	20	19.1	0.4	19.6	0.4
2.5617	20	20.9	0.5	21.9	0.4
2.7013	20	19.5	0.5	18.8	0.4

There is no information about the polarization of stars in the field around SN 2012bh. The standard analysis described in Section 2 is applied. The assumption of small interstellar polarization is quite justified. The supernova is located 70 degrees above the galactic equator and absorption in this direction is very small (Schlafly and Finkbeiner, 2011; Burstein and Heiles, 1982). Based on the data of Markkanen (1979) we conclude that the ISP does not exceed 1%. Moreover, according to Serkowski law, the value of galactic interstellar extinction indicates that the ISP in this direction is very small $P_{ISP} \leqslant 9E(B-V) = 0.12\%$ (Serkowski et al., 1975; Schlegel et al., 1998).

We derived the polarization degree on different days for two pairs of polarizers: Blagoveshchensk–Tunka and Blagoveshchensk–Kislovodsk. In both cases for every day the polarization was near zero. We averaged the polarization degree over all days for each pair of polarizers, then two values obtained were averaged too. The resulting $1-\sigma$ upper limit on linear polarization degree of SN 2012bh is 3%. QU diagram constructed for Blagoveshchensk–Tunka pair of polarizers is presented in Fig. 6.

5. BL Lac objects polarization observations

MASTER observations of blazars are collected in Table 4. For two of them, OC 457 and 3C 454.3, significant polarization was detected. To account for the polarization bias in a case of low signal/noise, we use a traditional statistic correction $P_{real} = \sqrt{P^2 - (\sigma_P)^2}$ (Serkowski, 1958). The final errors of P_{real} and θ involve the dispersions of corresponding values of field stars. Interstellar polarization P_{ISP} is calculated using the empirical law $P_{ISP} \leq 9E(B-V)$ (Serkowski et al., 1975; Schlegel et al., 1998). In all cases it is smaller than the dispersion of field stars polarization.

OC457 In the beginning of 2013 the activity of BL Lac object OC457 increased; in comparison with previous observations its brightness in the R filter went up a fifty-fold (Blinov et al., 2013). Its redshift is $z = 0.859$ (Barkhouse and Hall, 2001). Polarization observations were made by MASTER from February 4 to February 7 in Kislovodsk and Blagoveshchensk. Then the average magnitude of the object was 15.5^m in white light $(0.2B + 0.8R)$. The QU

Table 3
Photometry results for SN 2012bh by MASTER. P_W, P_E designate the west and east tubes of telescopes.

JD	Tunka				Blagoveshchensk				Kislovodsk			
	m_{P_E} (mag)	σ_{P_E} (mag)	m_{P_W} (mag)	σ_{P_W} (mag)	m_{P_W} (mag)	σ_{P_W} (mag)	m_{P_E} (mag)	σ_{P_E} (mag)	m_{P_W} (mag)	σ_{P_W} (mag)	m_{P_E} (mag)	σ_{P_E} (mag)
2456014	–	–	–	–	–	–	15.80	0.04	–	–	–	–
2456015	15.77	0.06	15.70	0.02	–	–	–	–	–	–	–	–
2456018	–	–	–	–	15.78	0.03	15.74	0.04	–	–	–	–
2456019	15.80	0.05	15.80	0.07	15.77	0.02	15.79	0.02	15.92	0.10	15.82	0.04
2456020	15.81	0.04	–	–	15.86	0.07	15.81	0.02	–	–	–	–
2456021	–	–	–	–	–	–	15.86	0.04	–	–	–	–
2456022	15.91	0.07	15.98	0.10	15.92	0.03	–	–	15.97	0.07	15.92	0.05
2456023	15.94	0.04	–	–	15.94	0.04	–	–	–	–	–	–
2456024	–	–	–	–	16.20	0.04	–	–	–	–	–	–
2456025	16.09	0.04	16.13	0.07	–	–	–	–	16.26	0.08	–	–
2456026	–	–	–	–	–	–	–	–	16.26	0.10	–	–
2456027	16.24	0.08	16.16	0.02	–	–	–	–	–	–	–	–
2456029	16.37	0.08	16.34	0.08	–	–	–	–	–	–	16.34	0.06
2456030	–	–	–	–	–	–	–	–	16.40	0.04	–	–
2456031	–	–	–	–	–	–	–	–	16.53	0.04	–	–
2456033	16.74	0.02	–	–	–	–	–	–	–	–	–	–

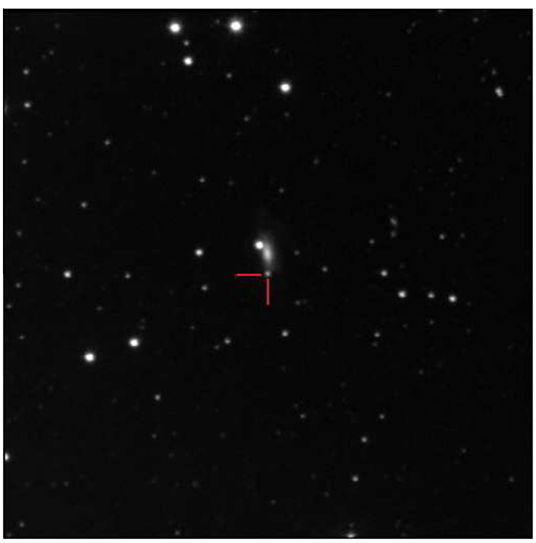

Fig. 4. Supernova 2012bh observed by MASTER Tunka on April 1, 2012.

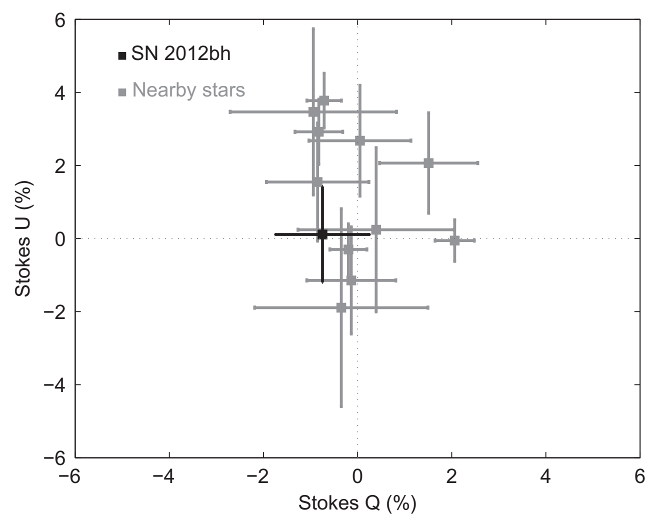

Fig. 6. QU diagram of the SN 2012bh (black point) and nearby stars (gray points). Stokes parameters are time-averaged results from Blagoveshchensk–Tunka pair of polarizers.

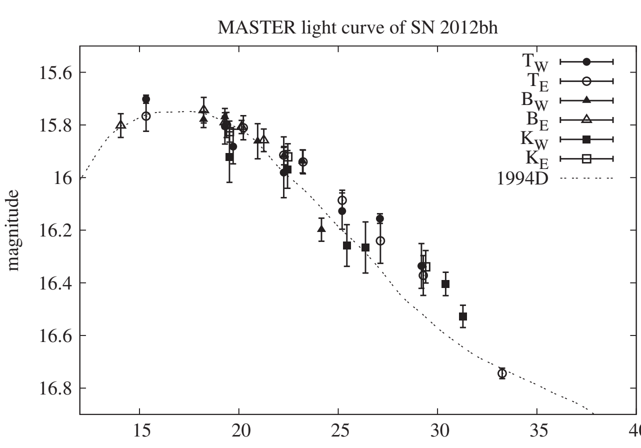

Fig. 5. Light curve of SN 2012bh recorded by MASTER. Tunka data are shown by circles; Blagoveshchensk, triangles; Kislovodsk, squares. Solid and empty signs correspond to different tubes with mutually perpendicular polarizers (W – west, E – east). The dashed curve is a fit by the light curve of SN 1994D.

diagram on February 7 is presented in Fig. 7. Using the measurements with four different position angles, we can find the fraction of polarized light with respect to a total intensity for each position angle. These flux differences are shown in Fig. 8. The χ^2 sinusoid fit yields the polarization degree and the polarization angle. There is a clear polarization present: $P = (21 \pm 2)\%, \theta = (87 \pm 5)^\circ$.

3C454.3 On the 24th of September Larionov and Efimova (2013) reported the start of activity of BL Lacertae object 3C 454.3. MASTER observed it on the night of the 25/26 September, in Kislovodsk, with 4 polarizers. The magnitude of the object was $\sim 14^m$ in white light. The polarization degree was very high $P = (34 \pm 2)\%$. The QU diagram and residual flux differences are presented in Figs. 9 and 10.

87GB165943.2 + 395846 and QSOB1215 + 303 For BL Lac object 87GB 165943.2+395846 the polarization degree was $P = (8 \pm 7)\%$ at the moment of observations (Fig. 11). On the night of MASTER observations BL Lac object 87GB 165943.2+395846 was fainter than 17^m in white light. For the BL Lac object QSO B1215+303 the polarization degree was $P = (4 \pm 2)\%$ at the moment of observations (Fig. 12); the magnitude of object was $\sim 15^m$ in white light. Apparently, these blazars were at quiescent states.

Table 4
List of blazars observed by MASTER in 2012–2013. K – Kislovodsk, KB – Kislovodsk and Blagoveshchensk.

Object	JD	Equatorial coordinates	P_{real}	θ (deg)	P_{ISP}
87GB 165943.2+395846	2456046.5	$17^h01^m24^s.635 + 39°54'37''.09$	8 ± 7	137 ± 10	0.25
QSO B1215+303	2456047.5	$12^h17^m52^s.082 + 30°07'00''.64$	4 ± 2	160 ± 13	0.2
OC 457 (K)	2456331	$01^h36^m58^s.595 + 47°51'29''.10$	21 ± 2	87 ± 5	1.2
OC 457 (KB)	2456331	$01^h36^m58^s.595 + 47°51'29''.10$	22 ± 2	92 ± 4	1.2
3C 454.3	2456561.5	$22^h53^m57^s.748 + 16°08'53''.56$	34 ± 2	13 ± 3	0.8

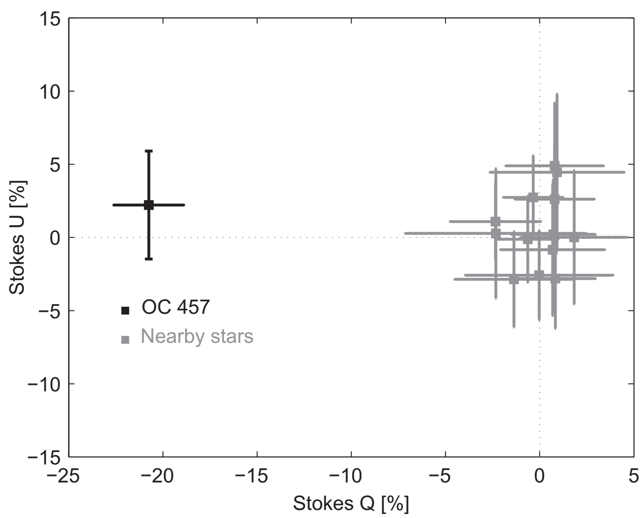

Fig. 7. QU diagram of the blazar OC 457 (black point) and nearby stars (gray points) observed by MASTER Kislovodsk on February 7, 2013.

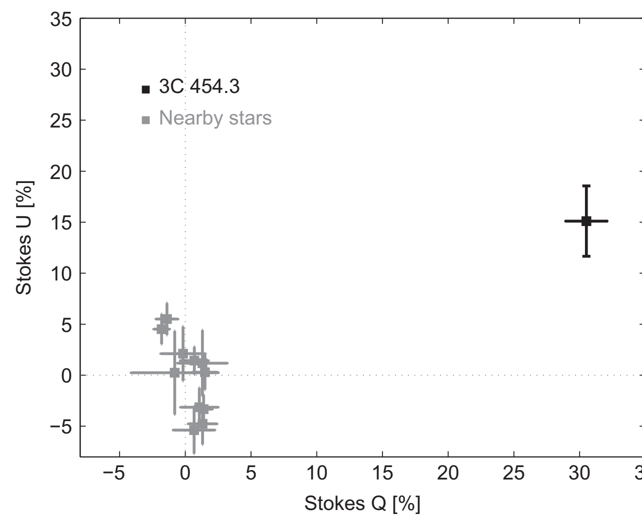

Fig. 9. QU diagram of the blazar 3C 454.3 (black point) and nearby stars (gray points) observed by MASTER Kislovodsk.

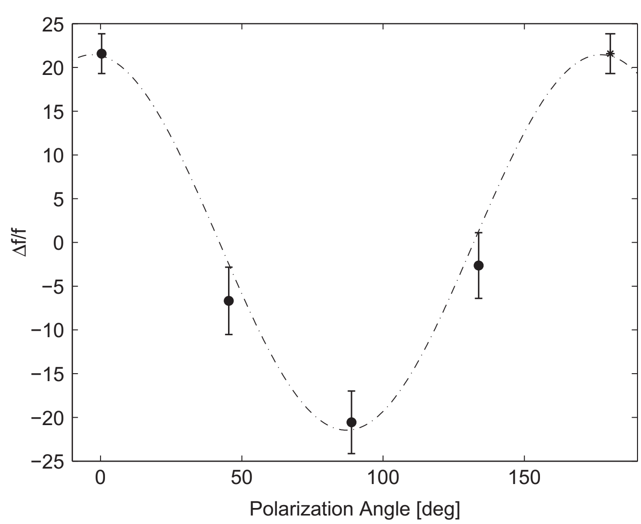

Fig. 8. Residual flux differences as measured through the polarizers at MASTER Kislovodsk for OC 457. The point at $\theta = 0°$ is a repeat of $\theta = 180°$. The dashed curve is the χ^2 sinusoid fit.

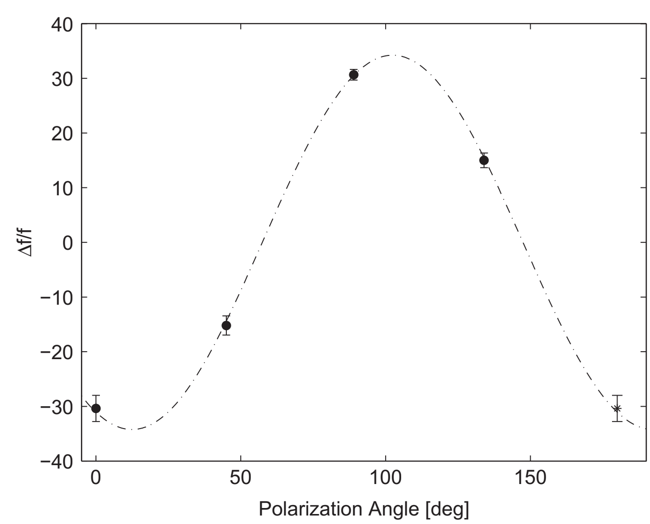

Fig. 10. Residual flux differences as measured through the polarizers at MASTER Kislovodsk for OC 457. The point at $\theta = 0°$ is a repeat of $\theta = 180°$. The dashed curve is the χ^2 sinusoid fit.

The results emphasize once again that MASTER polarizers are able to measure high polarization of bright objects ($< 16^m$).

Due to the subtraction of nearby field stars between tubes with differently oriented polarizers MASTER cannot use standard galactic polarized and unpolarized objects for calibration. Blazars are good candidates for calibration of MASTER polarization degree and angle. The polarization degree of blazars can reach very high values during their period of activity as well as their brightness. On the other hand, blazars are strongly variable sources. For calibration we need to obtain polarimetric data synchronously with other telescopes.

The degree of linear polarization and position angle of blazars OC 457 and 3C 454.3 agree with the results obtained by Larionov et al. (2013) and the data of the virtual observatory of the

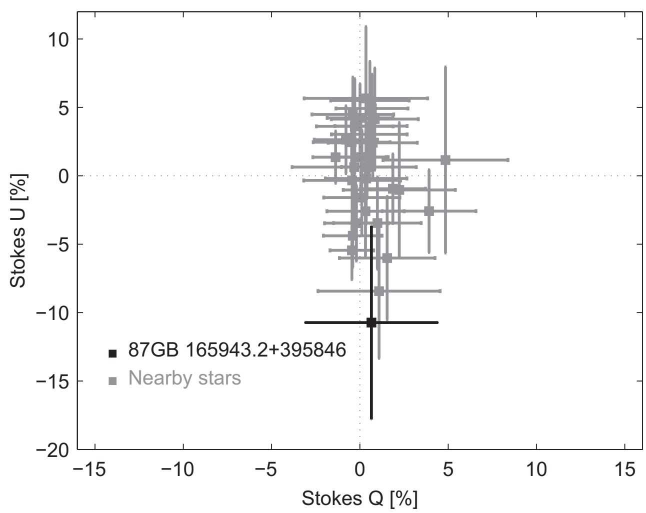

Fig. 11. QU diagram of the blazar 87GB 165943.2+395846 (black point) and nearby stars (gray points) observed by MASTER Kislovodsk.

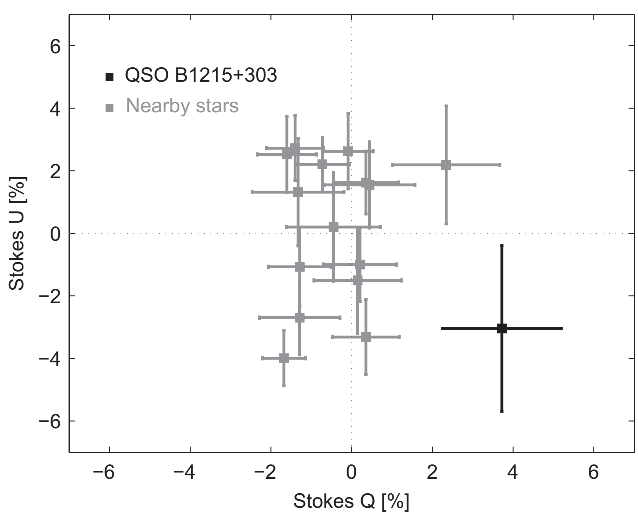

Fig. 12. QU diagram of the blazar QSO B1215+303 (black point) and nearby stars (gray points) observed by MASTER Kislovodsk.

Laboratory of Observational Astrophysics of the Sobolev Astronomical Institute[4] at the same observational dates.

6. Conclusions

In this paper, we described the goals and methods of polarimetric observations made with the MASTER robotic net. There is a number of different classes of astrophysical objects that manifest light polarization. Remarkably, most of them are the sites of high-energy phenomena. In the paper we present observations of gamma-ray bursts, one supernova, and several blazars.

The polarization observations of blazars show that MASTER's polarizers can be successfully used to measure a linear polarization degree above 5–10% with position angle accuracy of 3–10 degrees depending on brightness. Observing blazars with MASTER benefits also us as a source of calibration for the MASTER polarization measurements.

The polarization measurements are necessary for understanding the physics of GRBs jets: their geometry, magnetic field, microphysics, and emission mechanisms. However, GRBs prompt optical emission polarization has not been registered yet; there are only several measurements of afterglow polarizations.

For GRB100906A, GRB110422A, and GRB121011A, we present the polarization measurements of the prompt optical emission. Unfortunately, in each case, only two orthogonal polarizers took part in observations, thus only a lower limit on polarization is deduced and the position angle remains undefined. The dimensionless Stokes parameter is estimated to be less than an observational error for single objects, which equals to 2% in MASTER observations. We notice that the typical dispersion of the Stokes parameter of field stars in MASTER observations is 5%. Thus, MASTER telescopes can safely register linear polarization in excess of 10% and marginally detect polarization just above 5%. A level of 10% for the degree of linear polarization is predicted by some theoretical models of GRB emission.

The supernova phenomena can last several months. It allows us to obtain long data series including polarimetry. The discovery of significant polarizations from Type Ia supernovae will be an independent argument for the model of merging white dwarfs as one of the evolutionary path to such supernovae. Moreover, if some of SNe Ia are suspected to be asymmetric, it will raise a question about their suitability for cosmology as precise standardizable candles. Recent data shows modest continuum polarization (less than 1%) of SNe Ia but stronger line polarization ($\sim 2\%$). Low continuum polarization of SNe Ia light could indicate that the explosion is nearly spherical. But theoretical predictions on the polarization degree from asymmetric explosions are strongly model dependent. Furthermore, observed polarization can be contaminated by interstellar polarization in our Galaxy and in the host galaxies. It is important to remind that the present number of supernovae with good measurements of polarization prior to maximum light is still not enough to make a conclusion about the explosion geometry in this class of supernovae.

We present photometry in polarizers of Type Ia SN 2012bh observed by MASTER from March 27 to April 15. The light curve of SN 2012bh looks similar to the light curve of the "normal" Type Ia SN 1994D. The analysis of the light curve shows that the maximum brightness was on March 31. The resulting $1-\sigma$ upper limit on the linear polarization degree of SN 2012bh is 3%. Further spectropolarimetric and polarimetric observations of SNe Ia are needed to investigate explosion geometry and matter distribution around supernova and along the line of sight.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.newast.2013.12.003.

[4] http://lacerta.astro.spbu.ru/program.html.

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