Evolving optical polarization of the black hole X-ray binary MAXI J1820+070

Alexandra Veledina\textsuperscript{1,2,3}, Andrei V. Berdyugin\textsuperscript{1}, Ilia A. Kosenkov\textsuperscript{1,4}, Jari J. E. Kajava\textsuperscript{5}, Sergey S. Tygankov\textsuperscript{1,3}, Vilppu Piironi\textsuperscript{1}, Svetlana V. Berdyugina\textsuperscript{6,7}, Takeshi Sakanoi\textsuperscript{8}, Masato Kagitan\textsuperscript{8}, Vadim Kravtsov\textsuperscript{4}, and Juri Poutanen\textsuperscript{1,2,3}

\textsuperscript{1} Department of Physics and Astronomy, FI-20014 University of Turku, Finland
e-mail: alexandra.veledina@gmail.com
\textsuperscript{2} Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullbacken 23, SE-10691 Stockholm, Sweden
\textsuperscript{3} Space Research Institute of the Russian Academy of Sciences, Profsoyuznaya Str. 84/32, 117997 Moscow, Russia
\textsuperscript{4} Department of Astrophysics, St. Petersburg State University, Universitetskaya pr. 28, Peterhof, 198504 St. Petersburg, Russia
\textsuperscript{5} Finnish Centre for Astronomy with ESO (FINCA), FI-20014 University of Turku, Finland
\textsuperscript{6} Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany
\textsuperscript{7} Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, 96822-1897 HI, USA
\textsuperscript{8} Graduate School of Science, Tohoku University, Aoba-ku, 980-8578 Sendai, Japan

Received September 15, 1996; accepted March 16, 1997

ABSTRACT

\textbf{Aims.} The optical emission of black hole transients increases by several magnitudes during the X-ray outbursts. Whether the extra light arises from the X-ray heated outer disc, or the inner hot accretion flow, or the jet is currently debated. Optical polarization measurements have a potential to disentangle the relative contributions of these components.

\textbf{Methods.} We present the results of BVR polarization measurements of the black hole X-ray binary MAXI J1820+070 during the period of March-April 2018.

\textbf{Results.} We detect small, \( \sim 0.7 \) per cent, but statistically significant polarization, a part of that is of the interstellar origin. Depending on the interstellar polarization estimate, the source intrinsic polarization degree is between \( \sim 0.3 \) and 0.7 per cent, and the polarization position angle is \( \sim 20^\circ \). We show that the polarization increases after MJD 58222 (2018 April 14). The change is of the order of 0.1 per cent and is most pronounced in the \textit{R} band. The change of the source Stokes parameters occurs simultaneously with the drop of the observed \textit{V}-band flux and a slow softening of the X-ray spectrum. The Stokes vectors of intrinsic polarization before and after the drop are parallel, at least, in the \textit{V} and \textit{R} filters.

\textbf{Conclusions.} We suggest the increased polarization is due to the decreasing contribution of the non-polarized component which we associate with the the hot flow or jet emission. The low polarization can result from the tangled geometry of magnetic field or from the Faraday rotation in the dense, ionized and magnetized medium close to the black hole. The polarized optical emission is likely produced by the irradiated disc or scattering of its radiation in the optically thin outflow.

\textbf{Key words.} polarization – stars: black holes – stars: individual: MAXI J1820+070 – X-rays: binaries

1. Introduction

The black hole X-ray binaries play a key role in understanding the processes of accretion onto and ejection from the compact objects in the presence of a strong gravitational field. These sources evolve through the cycle of the bright outbursts proceeding on time scales of weeks to months, separated by long, years to decades, periods of quiescence (see Remillard & McClintock 2006; Done et al. 2007, for reviews). Their typical X-ray luminosities at the outburst peak are \( \sim 10^{37} - 10^{39} \) erg s\(^{-1}\), and typical distances are a few kpc. There are a few exceptional sources which reached or exceeded fluxes of 1 Crab in the X-rays: A 0620–00 (Kuulkers 1998), V404 Cyg (Makino et al. 1989, Rodriguez et al. 2015, Motta et al. 2017), and V4641 Sgr (Hjellming et al. 2000, Revnivtsev et al. 2002).

The X-ray transient MAXI J1820+070 was first detected on 2018 March 11 (Kawanura et al. 2018) by the Monitor of All-sky X-ray Image (MAXI, Matsuoka et al. 2009) and was associated with the optical transient ASASSN-18ey (Denisenko 2018). In the X-rays, the source flux exceeded 3 Crabs (Bozzo et al. 2018, Mereminskii et al. 2018) and in the optical the source reached magnitude \( m_V = 12 - 13 \) (Littlefield 2018, Russell et al. 2018). The parallax of the source \( \pi = 0.3 \pm 0.1 \) mas was presented in the Gaia DR2 catalog (Gaia Collaboration et al. 2018). This corresponds to the distance of \( 3.9^{+3.5}_{-1.3} \) kpc (Gandhi et al. 2018). This unusually bright event allows detailed investigation of multiwavelength spectral and timing properties. The course of the outburst was monitored in radio (Trushkin et al. 2018, Polisensky et al. 2018), sub-mm (Tetarenko et al. 2018a), optical (Baglio et al. 2018), X-rays (Uttley et al. 2018) and \( \gamma \)-rays (Bozzo et al. 2018, Kuulkers et al. 2018). The fact that the object was sufficiently bright even for small telescopes lead to the almost-continuous monitoring of the target and resulted in a rich variety of the observed phenomena. Fast variability and powerful flares in the optical and infrared (Littlefield 2018, Sako et al. 2018, Gandhi et al. 2018a, Casella et al. 2018), optical and X-ray quasi-periodic oscillations (Mereminskii et al. 2018, Yu et al. 2018a, Buisson et al. 2018, Yu et al. 2018a, Zampieri et al. 2018), as well as low linear polarization (Berdyugin et al. 2018) were detected in the source. The 17 h photometric period was recently reported...
Patterson et al. (2018), tentatively associated with the orbital or superhump period (previously, the source showed a 3.4 h periodicity, Richmond 2018). The X-ray spectral and timing properties, as well as the optical/X-ray flux ratio suggest the source is a black hole binary (Baglio et al. 2018; Mereminskii et al. 2018).

The origin of optical emission of black hole transients in the outburst is still debated (see Poutanen & Veledina 2014). The optical flux can be produced in the outer disc irradiated by the central X-ray source, in the jet and in the inner hot accretion flow. The accurate measurements of optical polarization at different outburst stages with simultaneous studies of the optical and X-ray spectral and timing properties will hopefully help to disentangle the relative contributions of these components. In this work, we present the results of our polarization campaign with the highly sensitive Dipol-2 instrument (Pirola et al. 2014), obtained at the initial stages of the outburst. We show that the source demonstrates small but statistically significant intrinsic polarization, and study its spectral and temporal properties. We describe the obtained data in Sect. 2, present the results in Sect. 3, discuss them within the accretion-ejection framework in Sect. 4 and summarize our findings in Sect. 5.

2. Data

2.1. Optical polarimetric observations

Polarimetric observations of MAXI J1820+070 were performed with the Dipol-2 polarimeter (Pirola et al. 2014) on the remotely controlled Tohoku 60 cm (T60) telescope at Haleakala Observatory, Hawaii. To achieve the high accuracy of polarimetric measurements, the Dipol-2 exploits the 'double-image' design, which effectively eliminates the errors arising due to variations in seeing and transparency. The optical beam from the star is split into two parallel, orthogonally polarized beams (e- and o-rays) giving rise to two stellar images that are recorded simultaneously in two separated parts of each of three (BVR) CCDs. The two orthogonally polarized beams from the sky overlap on each image, and the total sky intensity is recorded in both of them. The stellar fluxes in both images are then extracted via aperture photometry. Because the sky intensities are equal for both images, its polarization is automatically cancelled. The resulting stellar polarization is completely free from systematic errors caused by sky polarization, even if it is variable over the observing run.

The observations were conducted for 12 nights from 2018 March 17 till April 25 (MJD 58195–58234). At every observing night, 10 to 48 measurements of Stokes parameters $q$ and $u$ have been made simultaneously in the BVR-filters and the average nightly values of polarization, $P$, and polarizing angle, PA, have been computed. The instrumental polarization has been determined from the observations of more than 20 non-polarized nearby stars. The magnitude of instrumental polarization for the T60 telescope is less than 0.01 per cent and, therefore, negligible in this case. The zero-point of PA has been measured using observations of highly polarized standards HD25433 and HD161056. A detailed description of the observation procedure, calibration and the data treatment techniques is given in Kosenkov et al. (2017). The nightly averages of our polarimetric observations of MAXI J1820+070 are listed in Table 1 and shown in Fig. 1.

2.2. X-ray data

A very good coverage of the initial stages of the outburst was obtained thanks to the Neil Gehrels Swift Observatory (Gehrels et al. 2004). The source was observed both in the soft (0.5–10 keV) and the hard (15–50 keV) X-ray ranges using the XRT telescope (Burrows et al. 2005) and the BAT monitor (Barthelmy et al. 2005), respectively. Due to very high brightness of the source, all XRT observations were performed in Windowed Timing (WT) mode. The extraction of the spectrum was done using the online tools (Evans et al. 2008) provided by the UK Swift Science Data Centre. Only zero grade (single pixel) events were included into the products.

The source flux in each XRT observation was determined based on the results of spectral fitting with the xspec package assuming the power-law model modified by the photoelectric absorption (model phabs*po). Because of the known calibration uncertainties at low energies, we restricted our spectral analysis to the 0.5–10 keV band. In the hard X-ray band (15–50 keV) we used results from the BAT transient monitor (Krimm et al. 2010).

Fig. 1. Evolution of the polarization degree and polarization angle of MAXI J1820+070 in different filters: B (blue triangles), V (green diamonds) and R (red crosses). For clarity, 0.5 d was added to MJD of B-filter and subtracted from MJD of V-filter. The vertical dashed line marks MJD 58222.

1 http://www.swift.ac.uk/user_objects/
2 http://www.swift.ac.uk/analysis/xrt/digest_cal.php
3 http://swift.gsfc.nasa.gov/results/transients/index.html
Table 1. Polarimetric data for MAXI J1820+070.

| MJD    | $P$ (%) | $\text{PA} (\degree)$ | $P$ (%) | $\text{PA} (\degree)$ | $P$ (%) | $\text{PA} (\degree)$ |
|--------|---------|------------------------|---------|------------------------|---------|------------------------|
| 58195.61983 | 0.78 ± 0.02 53.9 ± 0.8 0.70 ± 0.03 | 53.9 ± 1.2 0.77 ± 0.02 54.7 ± 0.8 |
| 58199.61832 | 0.71 ± 0.03 55.5 ± 1.4 0.86 ± 0.05 | 51.1 ± 1.8 0.74 ± 0.03 51.8 ± 1.3 |
| 58206.61784 | 0.75 ± 0.02 54.0 ± 0.6 0.77 ± 0.02 | 55.8 ± 0.8 0.75 ± 0.02 54.8 ± 0.6 |
| 58208.61502 | 0.79 ± 0.02 53.3 ± 0.7 0.80 ± 0.03 | 57.6 ± 1.0 0.76 ± 0.02 54.8 ± 0.8 |
| 58220.61279 | 0.79 ± 0.02 51.5 ± 0.9 0.83 ± 0.04 | 53.0 ± 1.3 0.77 ± 0.03 49.9 ± 1.0 |
| 58221.59912 | 0.75 ± 0.02 54.8 ± 0.8 0.84 ± 0.02 | 54.3 ± 0.8 0.78 ± 0.02 51.7 ± 0.8 |
| 58222.58917 | 0.81 ± 0.06 57.4 ± 2.0 0.86 ± 0.08 | 53.3 ± 2.8 0.76 ± 0.11 40.4 ± 4.0 |
| 58225.59632 | 0.62 ± 0.08 57.5 ± 3.6 0.68 ± 0.11 | 54.5 ± 4.6 0.76 ± 0.13 50.3 ± 4.9 |
| 58227.57404 | 0.76 ± 0.04 53.0 ± 1.7 0.87 ± 0.08 | 47.2 ± 2.6 0.84 ± 0.06 47.9 ± 2.0 |
| 58231.60084 | 0.74 ± 0.03 50.8 ± 1.2 0.83 ± 0.04 | 52.0 ± 1.5 0.88 ± 0.03 45.1 ± 1.0 |
| 58232.60051 | 0.76 ± 0.02 51.4 ± 0.9 0.91 ± 0.04 | 50.1 ± 1.2 0.90 ± 0.03 45.7 ± 1.0 |
| 58234.60428 | 0.86 ± 0.08 46.5 ± 2.6 0.9 ± 0.14 | 54.5 ± 4.4 0.87 ± 0.10 42.5 ± 3.7 |

Fig. 2. (a) MAXI J1820+070 outburst light curves at the initial stages as determined by the Swift/BAT (black error bars) and the Swift/XRT (blue error bars) in the 15–50 keV and 0.5–10 keV bands, respectively. (b) Evolution of the photon index as seen by the Swift/XRT. The vertical line marks MJD 58222.

Fig. 3. Light curve of MAXI J1820+070 in the $V$ filter (green line with error bars, from AAVSO observations). Polarization measurements are overplotted with pale-coloured symbols. As in Fig. 1 the dates for polarization measurements in $B$ and $V$ filters are shifted by 0.5 d for clarity. The vertical line marks MJD 58222.

The MAXI data have a big gap close in time to our observations, therefore, we do not use them further in our analysis.

2.3. Optical photometry

We make use of the public AAVSO $V$-band light curves. For each day we calculate the averaged magnitude and the standard error of the mean, which we report as the magnitude error (see dark green line in Fig. 3). We also extract the $BVR$ relative fluxes of MAXI J1820+070 and a close field star taken during our polarization measurements. Although such photometric measurements suffer from the uncertainties related to possible changes of the comparison star flux, the $V$-band light curve is found to be in good agreement with the AAVSO light-curve. We additionally retrieve the Swift/UVOT $U$-filter light curves, but in most of these observations MAXI J1820+070 shows signs of saturation, and thus we do not consider these data in the paper.
The light curves of polarization degree and PA in three filters are shown in Fig. 4. A small, yet significant polarization at a level of ~0.7 per cent is detected in the source direction, with a hint of an increase towards the end of observations. The PA initially remains the same within the errors, but after MJD 58222 there is a clear trend of its decrease.

In order to understand the nature of the observed variability, we compare the variation of polarization with photometric V-band and X-ray light curves. The observed total flux of ∼10^{-7} erg s^{-1} cm^{-2} in the 0.3–10 and 15–50 keV bands (see Fig. 3) and the distance estimate from the Gaia DR2 data (~4 kpc, Gandhi et al. 2018b), allow us to roughly estimate the luminosity at the peak of the outburst Lx ∼2 × 10^{38} erg s^{-1}. In spite of this rather high luminosity, the source remained in the hard/low state as evidenced by the measured X-ray spectral slope (Fig. 2a). The spectral index was stable before MJD 58222, but started to increase after that. Furthermore, we see a substantial drop of V-band flux around the same date (from AAVSO data, Fig. 3), when we detect the departure of the PA from ~55°. We find a similar decrease in all filters of our BVR photometric light curves. On the contrary, the X-ray flux was decaying smoothly around that date, suggesting a decoupling of the X-ray and optical fluxes (as also acknowledged by Townsend et al. 2018).

To check the dependence of polarization properties on time we split the observations into two parts, separated by MJD 58222. We calculate the average of those (see Table 1) and plot them in Fig. 4 in the Stokes parameters plane. The vectors of an additional polarization component in the V and R bands are nearly parallel. This suggests that the evolution is caused by an emerging polarized component.

The evolution is apparent in all bands. The statistical significance of change in q and u Stokes parameters can be estimated using multivariate Hotelling’s T^2 test (Hotelling 1931). The values for r_{p} are 12.8, 35.9 and 150 for B, V and R filters, respectively. The sizes n = n_1 + n_2 of the corresponding data sets are 398, 413 and 415, where n_1 and n_2 are the number of observations used to calculate average polarization before and after MJD 58222, respectively. The corresponding values of the variable f = (n − 3)r_{p}^2/[2(n − 2)] (which follows F-distribution with parameters 2 and n − 3) are 6.4, 17.9, and 74.7, which give the probabilities that polarization has not changed 2 × 10^{-3} (i.e. above 3σ), 3.5 × 10^{-2} and 2 × 10^{-28} (see Kosenkov et al. 2017 for details of application of the Hotelling’s T^2 test to the polarization data). To check that the evolution of polarization is not caused by instrumental effects, we compute the average polarization of a field star (star 1 in Table 2) before and after MJD 58222 and obtain the polarization degrees agree well within errors.

The spectral dependence of polarization degree and PA of the source before and after the MJD 58222 are shown in Figs 5 and 6 respectively. Each line corresponds to the average over night measurement. The spectral dependence of polarization degree and PA in Fig. 5 is almost flat, in contrast to Fig. 6 which shows a clear skew towards the R-band.

### 3.1. Evolution of the observed polarization

The light curves of polarization degree and PA in three filters are shown in Fig. 4. A small, yet significant polarization at a level of ~0.7 per cent is detected in the source direction, with a hint of an increase towards the end of observations. The PA initially remains the same within the errors, but after MJD 58222 there is a clear trend of its decrease.

In order to understand the nature of the observed variability, we compare the variation of polarization with photometric V-band and X-ray light curves. The observed total flux of ∼10^{-7} erg s^{-1} cm^{-2} in the 0.3–10 and 15–50 keV bands (see Fig. 3) and the distance estimate from the Gaia DR2 data (~4 kpc, Gandhi et al. 2018b), allow us to roughly estimate the luminosity at the peak of the outburst Lx ∼2 × 10^{38} erg s^{-1}. In spite of this rather high luminosity, the source remained in the hard/low state as evidenced by the measured X-ray spectral slope (Fig. 2a). The spectral index was stable before MJD 58222, but started to increase after that. Furthermore, we see a substantial drop of V-band flux around the same date (from AAVSO data, Fig. 3), when we detect the departure of the PA from ~55°. We find a similar decrease in all filters of our BVR photometric light curves. On the contrary, the X-ray flux was decaying smoothly around that date, suggesting a decoupling of the X-ray and optical fluxes (as also acknowledged by Townsend et al. 2018).

To check the dependence of polarization properties on time we split the observations into two parts, separated by MJD 58222. We calculate the average of those (see Table 1) and plot them in Fig. 4 in the Stokes parameters plane. The vectors of an additional polarization component in the V and R bands are nearly parallel. This suggests that the evolution is caused by an emerging polarized component.

The evolution is apparent in all bands. The statistical significance of change in q and u Stokes parameters can be estimated using multivariate Hotelling’s T^2 test (Hotelling 1931). The values for r_{p} are 12.8, 35.9 and 150 for B, V and R filters, respectively. The sizes n = n_1 + n_2 of the corresponding data sets are 398, 413 and 415, where n_1 and n_2 are the number of observations used to calculate average polarization before and after MJD 58222, respectively. The corresponding values of the variable f = (n − 3)r_{p}^2/[2(n − 2)] (which follows F-distribution with parameters 2 and n − 3) are 6.4, 17.9, and 74.7, which give the probabilities that polarization has not changed 2 × 10^{-3} (i.e. above 3σ), 3.5 × 10^{-2} and 2 × 10^{-28} (see Kosenkov et al. 2017 for details of application of the Hotelling’s T^2 test to the polarization data). To check that the evolution of polarization is not caused by instrumental effects, we compute the average polarization of a field star (star 1 in Table 2) before and after MJD 58222 and obtain the polarization degrees agree well within errors.

The spectral dependence of polarization degree and PA of the source before and after the MJD 58222 are shown in Figs 5 and 6 respectively. Each line corresponds to the average over night measurement. The spectral dependence of polarization degree and PA in Fig. 5 is almost flat, in contrast to Fig. 6 which shows a clear skew towards the R-band.

### 3.2. Interstellar polarization

The upper limit for the ISM polarization in the direction of MAXI J1820+070 can be estimated from the reddening of the source (Serkowski et al. 1975). The colour excess in the direction of MAXI J1820+070 is only E(B−V) = 0.19 mag as given by the IRSA database, while the estimate from the hydrogen column density gives E(B−V) = 0.163 ± 0.007 (Baglio et al. 2018). Hence, the expected ISM polarization degree is P_{ISM} < 9 × E(B−V) = 1.71 or 1.46 per cent for the two estimates.

To have a more accurate estimate of the contribution from the ISM polarization to that observed from MAXI J1820+070, we
study the field stars polarization. The resulting measurements for nearby field stars are given in Table 2. The V-filter sky map of the field around MAXI J1820+070, together with the polarization vectors of the field stars and the average values of the source before and after MJD 58222, are shown in Fig. 7.

We compare the observed polarization degree and PA of MAXI J1820+070 with those of the field stars. All stars have Gaia DR2 counterparts, allowing comparison of their polarization properties as a function of distance (parallax). The polarization degree and PA of the field stars are almost independent of distance (see Figs 8 and 9). The source shows $B$ and $V$ band polarization degree roughly consistent with the field stars and a significantly different degree in the $R$-band. The polarization angles substantially deviate from the nearby field stars in all bands.

In Fig. 10 we plot the normalized Stokes parameters of MAXI J1820+070 and the field stars. In all three filters the Stokes vectors of the source cluster in a separate from the field stars region of the $q-u$ plane. The difference is most prominent in the $R$ band, where the MAXI J1820+070 points are totally isolated. This points towards substantial intrinsic polarization of MAXI J1820+070 during the entire duration of observations.

To better emphasize it, we plot the average $P$ and PA in Fig. 11: the blue dashed lines correspond to the average for observations made before MJD 58222 and the red solid line corresponds to the average computed after that date. The spectral distributions of field stars are shown with the grey dotted lines. We note that the flat polarization degree and PA spectral distribution of the source is very similar to that of the field stars before MJD 58222. However, the absolute value of the source PA is different from those of the field stars in all observations. Furthermore, the spectral dependence of the polarization degree observed after MJD 58222 is skewed towards $R$ and has a strong
Table 2. Polarimetric data for the field stars and their weighted average.

| Star | \( \pi \) (mas) | \( P \) (%) | \( P \) (B) | \( P \) (%) | \( P \) (V) | \( P \) (%) | \( P \) (R) | \(\text{PA} \) (°) |
|------|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|----------------|
| 1    | 0.76 ± 0.02     | 0.80 ± 0.06 | 60.4 ± 2.1  | 0.60 ± 0.06 | 63.7 ± 2.7  | 0.69 ± 0.05 | 65.1 ± 1.9  |
| 2    | 0.23 ± 0.04     | 0.75 ± 0.24 | 82.3 ± 8.7  | 0.74 ± 0.17 | 71.9 ± 4.4  | 0.65 ± 0.10 | 69.9 ± 4.5  |
| 3    | 0.15 ± 0.03     | 0.81 ± 0.16 | 67.3 ± 5.5  | 0.82 ± 0.13 | 73.0 ± 4.9  | 0.51 ± 0.07 | 75.5 ± 4.1  |
| 4    | 1.76 ± 0.03     | 0.49 ± 0.11 | 70.7 ± 6.6  | 0.79 ± 0.13 | 81.4 ± 4.1  | 0.61 ± 0.07 | 75.0 ± 3.2  |
| 5    | 1.08 ± 0.03     | 0.81 ± 0.09 | 68.6 ± 3.2  | 0.80 ± 0.12 | 62.3 ± 4.9  | 0.50 ± 0.05 | 62.9 ± 3.0  |
| 6    | 0.35 ± 0.02     | 0.80 ± 0.08 | 59.8 ± 3.0  | 0.64 ± 0.11 | 64.9 ± 2.8  | 0.68 ± 0.04 | 66.2 ± 1.7  |
| 7    | 0.44 ± 0.05     | 0.82 ± 0.04 | 64.9 ± 1.4  | 0.70 ± 0.04 | 67.6 ± 1.6  | 0.67 ± 0.03 | 64.1 ± 1.1  |
| 8    | 0.82 ± 0.12     | 0.72 ± 0.07 | 65.6 ± 2.7  | 0.67 ± 0.07 | 64.9 ± 2.8  | 0.68 ± 0.04 | 66.2 ± 1.7  |
| 9    | 0.38 ± 0.02     | 0.74 ± 0.09 | 62.1 ± 3.3  | 0.71 ± 0.07 | 71.8 ± 2.8  | 0.53 ± 0.04 | 60.7 ± 1.9  |
| 2,3,6,7,9 | 0.80 ± 0.03  | 64.2 ± 1.2  | 0.70 ± 0.03 | 68.6 ± 1.3  | 0.60 ± 0.02 | 64.1 ± 0.9  |

Fig. 9. Same as in Fig. 8 but for the polarization angle.

dependence of PA on wavelength. This is in contrast to that observed in the field stars. This further supports the suggestion that there is a substantial polarization of the source of the origin other than interstellar.

We estimate the contribution of the ISM polarization to that of the source in two ways. We first take a star which is closest in angular separation from MAXI J1820+070 and is reasonably close in parallax and use its polarimetric characteristics as a proxy for ISM polarization. In our case, this is star 2 from Table 2. As an alternative, we take a set of stars close to the source and average their polarimetric measurements. For that we chose five closest in parallaxes (0.15–0.5 mas) stars from Table 2 and calculate the weighted average of their Stokes vectors, with the weights being inversely proportional to the square of individual errors. The results are given in the bottom line of Table 2.

Fig. 10. Normalized Stokes parameters for MAXI J1820+070 (coloured symbols) and the field stars (black crosses) in the \( q - u \) plane. The pale and the saturated colours correspond to observations of MAXI J1820+070 made before and after MJD 58222, respectively. The size of the symbols grows with MJD.
The largest difference (about 2–3σ) between these average values and those for star 2 are in PA of B and V filters.

### 3.3. Intrinsic polarization

Using the estimates for the interstellar polarization, we compute the intrinsic polarization of the source. From the observed Stokes averages of the source we subtract the field stars sample mean and show the results in Fig. 12 for two cases: \( P_{\text{ISM}} \) estimate using the closest field star 2 and using the five-star average. The resulting estimates are given in Table 3.

For the five-star ISM polarization estimate (Fig. 12b), we find that the angle of intrinsic polarization is the same (within errors) for V and R bands and are different from that in the B band. The vectors of polarization change on the \( q-u \) plane are almost the same in both filters, but the Stokes vectors before/after MJD 58222 are not strictly parallel, implying a possible evolution of both polarization degree and angle between the observations.

If we estimate the interstellar contribution using the closest star 2 alone, we find the intrinsic PA of the source is consistent in all three photometric filters and for all dates, i.e. all data points lie very close to one line with the start in the origin. This result is striking, given the large error bars, which are mostly coming from the star 2 polarization uncertainties. This implies that the PA did not change, but rather the intrinsic polarization degree of the source has grown after MJD 58222.

The spectral dependence of intrinsic polarization for two cases of \( P_{\text{ISM}} \) estimation can be seen in Fig. 13. For the \( P_{\text{ISM}} \) estimate from star 2, the polarization degree peaks in V, while polarization angle is wavelength-independent. For the five-star estimate, the PA is smaller in B, while the polarization degree is flat before MJD 58222 and grows towards R after MJD 58222. In both cases, the maximal polarization increase is observed in R, some enhancement is also seen in V, but not in B filter.

### 4. Discussion

#### 4.1. Principal sources of optical polarization in accreting black holes

During the outburst of accreting black holes in low-mass X-ray binaries the optical luminosity is dominated by the accretion process and the contribution of the secondary star is negligible. There are, however, many spectral components that can contribute to the optical band and can also be polarized to some extent (see discussion in Veledina et al. 2013; Kosenkov et al. 2017). In the soft state, the outer parts of the standard accretion disc irradiated by the X-ray emission from the compact object likely dominate the optical flux (see e.g. Poutanen & Veledina 2014). In the hard state, there could be at least two additional optical components: the radio-emitting
The typical polarization is 10–20 per cent (Beloborodov 1998), however, the observed one will be diluted by the disc radiation. The non-thermal electrons accelerated within the hot inner jet (see review by Fender & Gallo 2014) and the inner hot flow that is believed to dominate in the X-rays (Veledina et al. 2013; Poutanen & Veledina 2014). All these components can be polarized.

The polarization degree from the accretion disc depends on the temperature structure of the atmosphere and the dominating source of the opacity. When the electron scattering dominates, the intrinsic polarization is <12 per cent in the optically thick case and is parallel to the disc plane, i.e. perpendicular to the disc normal (Chandrasekhar & Breen 1947; Chandrasekhar 1960; Sobolev 1949, 1963). In the optically thin case, polarization is parallel to the disc normal and can reach higher values (Sunyaev & Titarchuk 1985; Beloborodov & Poutanen 1999; Viironen & Poutanen 2004). The opacity by true absorption can significantly affect the polarization properties. It reduces the polarization degree and leads to a rotation of the polarization plane by 90° (relative to the case of pure scattering) at angles close to the disc normal, known as the Nagirner effect (Nagirner 1962; Dolginov et al. 1995; Gnedin & Silant’ev 1997). Strong wavelength dependence of the absorption opacity may result in the wavelength-dependent polarization degree. This is observed, for example, in Be stars (Poeckert & Marlborough 1978; Poeckert et al. 1979) as jumps in polarization at the edges of Balmer and Paschen series as well as in the corresponding lines.

Moreover, the discs in X-ray binaries are likely flared and/or tilted, hence the disc atmosphere local normal changes with distance to the central source. This may lead to smooth spectral dependence of polarization angle, as different parts of the disc dominate emission at different wavelengths.

The jets detected in the hard states can become a source of a variable in time polarized light (e.g. Zdziarski et al. 2014) due to the nature of synchrotron radiation in the ordered magnetic field. The polarization degree strongly depends on the magnetic field geometry in the emitting region. For a power-law distribution of electrons, the maximum polarization in the optically thin regime (expended in the optical) can reach 70–75 per cent, depending on the slope of the distribution (Rybicki & Lightman 1979). For a completely disordered field, the polarization drops to zero.

The non-thermal electrons accelerated within the hot inner accretion flow may also emit synchrotron radiation, which, in principle, can be polarized if the magnetic field structure has an ordered component (Veledina et al. 2013; Poutanen & Veledina 2014). However, the resulting optical polarization in this model is expected to be small because the magnetic field in the hot flow is expected to be rather tangled by the turbulent motions within the accretion flow. Furthermore, in the case of Galactic black holes, the Faraday rotation can significantly affect the observed polarization produced by both accretion flow and the jet. The rotation angle is \( \chi_{\mu} = 4 \times 10^{21} B_{10}^{-2/3} \lambda_{\mu} \), where \( \tau_{30} \) is the Thomson optical depth along the line of sight, \( B_{10} \) is the parallel component of the magnetic field in units of \( 10^6 \) G and \( \lambda_{\mu} \) is the wavelength in microns. Thus if the optical emission is produced in an extended region close to the black hole, the expected polarization is essentially zero.

Optical polarization can also be produced by scattering of the accretion disc radiation in the outflows from the accretion disc. For a mildly relativistic outflow with velocity \( v/c \) of tens of per cent, that could be associated with the base of the radio jet, the scattering produces polarization parallel to the jet axis (Beloborodov 1998). The maximum polarization is reached at inclination \( \cos \theta = v/c \). The typical polarization is 10–20 per cent (Beloborodov 1998), however, the observed one will be diluted by the disc radia-
4.2. Origin of polarized optical emission in MAXI J1820+070

The nature of the observed polarization of MAXI J1820+070 cannot be decisively associated with one of the components described above because of the small, below 1 per cent, intrinsic polarization degree. Additional information on its wavelength dependence, its variability as well as the broad-band spectral properties is required to understand the source of the polarized light.

4.2.1. Irradiated disc

Numerous spectroscopic observations show asymmetric lines which are skewed towards red, suggesting presence of a wind at the outburst initial stages (before ∼MJD 58193, Bahramian et al. 2018; Garnavich & Littlefield 2018; Munoz-Darias et al. 2018). Observations on MJD 58197 show the line profile has switched to a symmetric broad shape, resembling those observed in the accretion disc (Munoz-Darias et al. 2018). Interestingly, the optical spectrum is rather hard (e.g., Russell et al. 2018), and the simultaneous Swift UVOT and XRT light-curves were shown to correlate (data taken on MJD 58188, Paice et al. 2018) favoring a large contribution of the reprocessed radiation to the optical flux.

On the other hand, substantial variability present on the subsecond timescales (Gandhi et al. 2018), is not in line with the reprocessing scenario. The observed ULTRACAM (Dhillon et al. 2007) light-curves suggest that the variability has higher amplitude in r′, as compared to g′: the peaks are higher and the dips are deeper in r′. Hence, there are at least two components contributing to the optical emission: one of them is likely the irradiated disc, another is a jet or a hot flow. The analysis of the polarimetric data suggests one of them is polarized and the other is not. The drop in the V-flux by 50 per cent after MJD 58222, which coincides with the increase of polarization, implies that the unpolarized component has decreased.

We first consider the possibility that the irradiated disc corresponds to the unpolarized component. The V band is in the Rayleigh-Jeans part of the disc spectrum (Russell et al. 2018) and therefore depends nearly linearly on the disc temperature. This implies that the decrease of optical flux should result from a decrease of the corresponding irradiating X-ray flux by a factor of 5–6. On the contrary, there is a very little change in the X-ray flux around MJD 58222 (see Fig. 2). Thus, the irradiated disc cannot be the source of the unpolarized emission, but it can be the source of the stable polarized component. Indeed, the small polarization degree, as well as both flat and skewed towards R spectral dependence of PA can be explained in the disc scenario (the latter is due to the change of the disc atmosphere local normal).

4.2.2. Jet

Then we can ask whether the jet can contribute to the optical band and/or be a source of the polarized emission. The peak V-flux was about 95 mJy (assuming $A_V = 0.5$), while the jet flux at 227 and 343 GHz on MJD 58220 was 100 and 120 mJy, respectively (Tearetken et al. 2018). Thus, the jet could easily produce most of the observed optical flux. Increase in polarization together with the decrease in the optical flux then implies that the jet optical emission has to be unpolarized. On the other hand, if the jet emission is produced somewhat similarly to the emission of jets in blazars, it is expected to be intrinsically highly polarized (Impey, Lawrence, & Tapia 1991; Wills et al. 1992; Lister 2001; Marscher et al. 2002; Ikemjir et al. 2011). If the jet were the source of the polarized emission, we would expect the increase of polarization towards longer wavelength due to soft (red) jet spectrum, which is not observed.

The standard Blandford & Königl (1979) jet model is not capable of explaining the observed mid-IR excess (Russell et al. 2018). An additional jet component associated with instantaneous injection of relativistic electrons at the base of the jet and their fast cooling (Pacari & Casella 2009) may be responsible for that. It is natural to expect such a jet to emit polarized synchrotron emission because fast cooling episode occurs in a small part of the jet with some preferential magnetic field direction. This additional component with the power-law like spectrum contributes to the near-IR and optical bands, and extrapolating the power law we can estimate its contribution to the V-band flux on MJD 58195–58196 (see Russell et al. 2018) to be about 30 per cent. Thus, in principle, its evolution may be responsible for the observed drop in the V band. The requirement that this red component is polarized at the level much below one per cent then implies the jet magnetic field in the emitting region has to be highly tangled. It is not clear whether this can be incorporated into the current version of this jet model.

If, however, the emitting region is situated close to the central source, the Faraday rotation may destroy the polarization and satisfy the observational constraints. We thus conclude that the standard jet emitting in the radio and the fast-cooling plasma at the base of the jet can both contribute to the optical flux, but these components have to be unpolarized, implying either disordered magnetic field or a location close to the black hole where Faraday rotation depolarizes their emission.

4.2.3. Hot flow

The observed behaviour of varying red component and a stable blue component can be naturally explained in the hot accretion flow scenario (Veledina et al. 2013; Poutanen & Veledina 2014; Poutanen et al. 2014). In the hard state, we expect a contribution of the synchrotron emission from the inner hot flow, which can reproduce the observed red excess to the irradiated disc spectrum. On the transition to the soft state, when the truncation radius of the cold disc decreases, this component should decrease first in the red (where the emission from the outer parts of the hot flow contributes) and later in the blue. In the soft state, the optical emission is consistent with the irradiated disc as, for example, was seen in XTE J1550–564 (Poutanen et al. 2014).

It is interesting to note that the X-ray spectrum started to soften at about the same time as the V-flux dropped and polarization increased (Figs 2 and 3). Thus, if we interpret the softening as a start of the transition to the soft state, we expect a weakening of the red non-thermal hot flow component (Kalemeci et al. 2013; Poutanen et al. 2014), as observed. Because the hot flow
reduction of \( B \) minimum in this scenario. The wavelength dependence of the PA, which shows a larger increase of \( R \) contribution of the unpolarized emission from the hot flow. The blue dashed lines in Fig. 13a). In the \( R \)-band, there is a stronger contribution of the unpolarized emission from the hot flow. The larger increase of \( R \)-filter polarization can caused by the greater reduction of \( R \)-band hot flow emission, which is expected in this scenario.

If, on the other hand, we accept the five-star average as the ISM polarization estimate, the intrinsic polarization has a minimum in \( B \) (see red solid line in Fig. 13). This minimum can be understood as a contribution of unpolarized Balmer lines to this band. The wavelength dependence of the PA, which shows a deviation in \( B \) by about 10\(^{\circ}\) (see Fig. 13), can indicate the difference of local normal to the disc plane between the places where \( B \) and \( V/R \) emission is produced.

We note that the emission from the hot flow is produced by relativistic electrons injected by, for example, magnetic reconnection, with their subsequent fast cooling in the magnetic field. This means that the hot flow model and the fast-cooling base-of-the-jet model would produce similar spectra if the size of the emission region and the magnetic field are similar. The only difference is the direction of escaping particles down to the black hole within the flow or up to the jet. The latter cannot be probed so far. Therefore, it is currently impossible to differentiate between these models if the considered region of fast cooling in the jet is contained within the hot flow (i.e. when the jet anchors to the accretion flow).

The requirement that the photons are able to escape avoiding self-absorption within the source and to produce the mid-IR emission down to 0.1 eV determines its size of about 400 Schwarzschild radii (see eq. 13 in Veledina et al. 2013) for a 10\( M_\odot \) black hole. We conclude that the hot flow is a viable possibility to reproduce the mid-IR to optical unpolarized emission, while the polarized emission likely comes from the irradiated disc or scattering in the outflow.

4.3. Comparison to V404 Cyg

The exceptional brightness of MAXI J1820+070 is comparable to the recent black hole transient V404 Cyg, for which several high-precision (accuracy higher than 0.1 per cent) polarimetric observations were performed (Tanaka et al. 2016, Kosenkov et al. 2017). Intrinsic polarization measured using Dipol-2 instrument was found at a level below ~1 per cent similarly to those measured for MAXI J1820+070. The wavelength dependence of intrinsic polarization in V404 Cyg, with the possible peak in V, is similar to that obtained for MAXI J1820+070 using star 2 estimation for the ISM polarization.

The biggest difference is, however, that V404 Cyg was observed during a likely super-Eddington outburst, while MAXI J1820+070 was in the hard state, at a luminosity of about 10 per cent of Eddington. In V404 Cyg, there was evidence for a strong slow equatorial outflow, which was a likely source of polarization. Also scattering in a mildly relativistic outflow was suggested as an alternative model. Here, for MAXI J1820+070 the outflow model is also possible, because of the presence of the steady radio emission often observed in the hard states of accreting black holes. We can note that in both cases, a small polarization implies that the magnetic field in the emission region is rather disordered if the observed radiation is produced by synchrotron radiation in a jet or a hot flow and/or the Faraday rotation plays a significant role in decreasing the polarization. The wavelength dependence of the polarized emission implies a strong contribution of the wind or the irradiated accretion disc to the polarized flux.

5. Conclusions

We have presented the results of the observational campaign studying \( BVR \) polarization properties of the black hole X-ray binary candidate MAXI J1820+070. We found evidence for a small, about 0.7–0.9 per cent, but statistically significant polarization in the source, at PA\( \approx \) 50\(^{\circ}\) in all three filters. Such a high accuracy is possible thanks to the original design of the Dipol-2 instrument.

To determine the interstellar component of polarization, we performed polarimetric study of the field stars and found the ISM polarization degree of \( \sim 0.6–0.8 \) per cent at PA\( \approx \) 65 – 80\(^{\circ}\), depending on the way we estimate it. The resulting intrinsic source polarization degree is at a level of \( \sim 0.3 \) to 0.7 per cent at PA\( \approx \) 20\(^{\circ}\).

We found that the polarization degree increases by about 0.1 per cent after MJD 58222 in both \( V \) and \( R \) filters with additional change in \( V \) by 4 to 7.5 deg. In \( B \), an enhancement of polarization at a 3\( \sigma \) level is seen. The moment when the polarization started to significantly evolve coincides in time with the drop in the \( V \)-flux, suggesting that an increase in polarization is associated with the decreasing flux of the non-polarized component. We noted that at about the same date, the X-ray spectral index started to increase suggesting a start of the transition to the soft state.

We suggested that the jet or the hot flow contributes to the optical flux, but either of these components have to be unpolarized, implying a rather tangled magnetic field or a large role of the Faraday rotation that destroys polarization in the ionized magnetized medium close to the black hole. The likely source of the polarized emission is the outer irradiated accretion disc or the disc radiation scattered by the optically thin wind.

Acknowledgements

This research has been supported by the Ministry of Science and Higher Education of the Russian Federation grant 14.W03.31.0021. We acknowledge support from the Academy of Finland grants 309308 (AV) and 295114 (JJEK), ERC Advanced Grant HotMol ERC-2011-AdG-291659 (SVB, AVB). The Dipol-2 was built in cooperation by the University of Turku, Finland, and the Kiepenheuer Institut fuer Sonnenphysik, Germany, with support from the Leibniz Association grant SAW-2011-KIS-7. We are grateful to the Institute for Astronomy, University of Hawaii for the observing time allocated for us on the T60 telescope. The research has made use of MAXI data provided by RIKEN, JAXA and the MAXI team, the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and the data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral
