A quasi-periodicity in the optical polarization of the blazar PKS 2155-304

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Abstract. We report the detection of a quasi-periodic oscillation (QPO) in the polarized flux of the BL Lac PKS 2155-304 during a state of increased gamma-ray activity. Measurements were obtained with the HIgh Speed Photo-POlarimeter (HIPPO) of the South African Astronomical Observatory (SAAO) using a temporal resolution of 5 minutes. On 24 July 2009, the polarization degree appeared to be modulated by a periodic component. Simultaneous gamma-ray measurements with the High Energy Stereoscopic System (H.E.S.S.) showed that the quasi-periodicity coincided with an increase in the gamma-ray flux of the source. A periodogram of the polarized flux reveals the presence of a prominent peak at a frequency corresponding to a period of ∼30 minutes. This is the first detection of QPO activity in the optical polarization of an active galactic nucleus (AGN), potentially opening up a new method of studying the AGN phenomenon. Mechanisms capable of producing such a short timescale periodicity are briefly discussed.

1. Introduction

Active galactic nuclei (AGN) and Galactic black hole binaries (BHBs) are believed to be mass-scaled analogies, both powered by accretion of matter onto supermassive black holes (SMBH, with masses of $10^6-10^9 M_\odot$) and massive black holes ($\sim 10 M_\odot$ for BHBs). Observations of quasi-periodic oscillations (QPOs) are fairly common for BHBs and serve as an important diagnostic tool, e.g. providing accurate estimates of the black hole mass [1, 2]. On the contrary, very few claims of QPOs have been made for AGN, e.g. [3, 4]. PKS 2155–304 is one of a small number of AGN for which convincing evidence of quasi-periodic brightness variations have been found. The source is classified as a blazar, a subclass of radio-loud AGN for which the relativistic jet is oriented close to the line-of-sight of the observer [6]. PKS 2155–304 exhibits significant variability on timescales ranging from a few minutes [7] to years [8, 9]. Most recently, a ∼4.6 hour periodic component was detected in the $X-$ray light curve of the source [5]. Here, we report the possible discovery of a QPO in the polarized flux of PKS 2155–304. The optical polarization of the source was monitored for roughly three days in July 2009, during which amplitude fluctuations on timescales ranging from minutes to hours were detected. Gamma-ray observations were obtained independently over the same period, with indications of two $\gamma-$ray flares. In this paper we discuss the implications of the coincidence of these multi-wavelength measurements. A brief description of the polarization and very high energy (VHE, photons with energies above GeV) $\gamma-$ray observations is given in section 2, followed by the data analysis in section 3. The results are discussed in section 4 and a summary of our findings are presented in section 5.

2. Observations

A description of the polarization and gamma-ray variability of PKS 2155–304 in July 2009 follows.

2.1. Optical polarization

The optical polarization of PKS 2155–304 was measured with the HIgh-sPeed Photo-POlarimeter (HIPPO [10]), a rapidly rotating dual-channel photo-polarimeter operated by the South African Astronomical Observatory (SAAO). The instrument was mounted on the 1.9 m Radcliffe telescope of the SAAO. The intra-day variability (IDV) of the source was monitored from 25 – 27 July 2009 for a total of 9.23 hours, using a time-resolution of 5 minutes. The linear and circular polarization of the source was recorded in the $I-$ and $B-$band. Observations commenced one day after a VHE $\gamma-$ray flare was recorded with the High Energy Stereoscopic System (H.E.S.S.). A summary of the average polarization degree (or fractional polarization) and polarization angle[1] are presented in Table 1 which lists the modified Julian date (MJD), length of observation (T_{obs}) and the mean daily polarization degree and polarization angle (calculated by taking the average of the $I-$ and $B-$band measurements). The table demonstrates that the polarization degree increased from roughly 3% – 9% over a three day period (MJD = 55037 to 55038) and that the orientation of the polarization angle changed rapidly from 90° to 68° in the span of one day.

Table 1. The mean daily optical polarization of PKS 2155–304 in July 2009.

MJD	T_{obs} (min)	p (%)	θ (°)
55037	251	3.7 ± 0.3	88 ± 2.5
55038	105	7.0 ± 0.3	67 ± 1.0
55039	197	8.3 ± 0.7	68 ± 0.5

2.2. Gamma-rays

Our observations overlapped with an increase in the $\gamma-$ray activity of the blazar. The results from the long-term monitoring campaign of PKS 2155–304 with the High Energy Stereoscopic System [11] between 19 and 27 July shows two prominent increases in the VHE flux I above the threshold energy of 300 GeV, as illustrated in Fig. 1. The polarization degree is indicated by the square markers and is superimposed on the VHE light curve. The $\gamma-$ray flares (marked as Flare 1 and Flare 2 on Fig. 1) are detected above a median flux of 1.9×10^{-11} ph cm^{-2} s^{-1}, consistent with the baseline ($\sim 10^{-11}$ ph cm^{-2} s^{-1}) reflected by the long-term measurements of the source [11]. The first $\gamma-$ray flare lasts approximately four days from MJD = 55033 to 55037, peaking at $I = (8.0 \pm 0.4) \times 10^{-11}$ ph cm^{-2} s^{-1} on MJD = 55035 (or 23 July 2009). Immediately following this, another increase in the $\gamma-$ray brightness is seen (Flare 2). The VHE flux rises from $(1.9 \pm 0.4) \times 10^{-11}$ ph cm^{-2} s^{-1} to $(5.6 \pm 0.4) \times 10^{-11}$ ph cm^{-2} s^{-1} over three days (from MJD = 55037 to 55039), which could be indicative of a developing flare. However, we are unable to verify this since the 2009 H.E.S.S. campaign concluded on MJD = 55039.

[1] The polarization angle is measured from the North Celestial Pole towards the Celestial East.

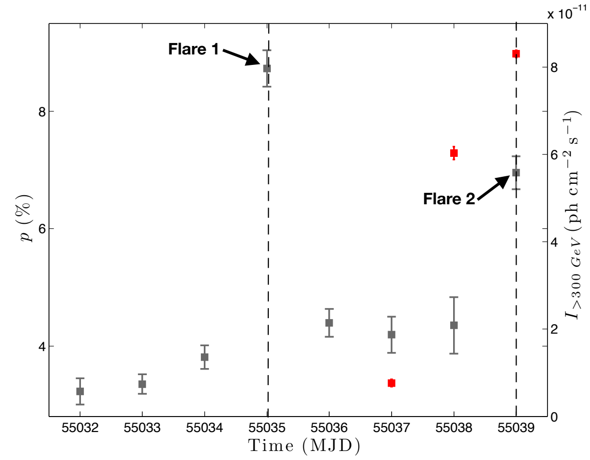

Figure 1. The $\gamma-$ray flux I of PKS 2155–304 during July 2009 for photons with energies > 300 GeV. Two prominent increases in the $\gamma-$ray flux are detected, marked as "Flare 1" and "Flare 2" respectively. For Flare 2 we have simultaneous polarization measurements. The $I-$band polarization degree p is represented by the red symbols and are superposed on the VHE light curve (indicated by the grey symbols). Note that the increase in the fractional polarization precedes the increase in $\gamma-$ray flux of Flare 2. The left scale shows p (%), while the scale on the right shows I (ph cm^{-2} s^{-1}).

3. Data Analysis

The daily polarization degree and $\gamma-$ray flux of PKS 2155–304, as well as amplitude fluctuations in the intra-day polarization degree, are examined below.

3.1. Simultaneous polarization and $\gamma-$ray measurements

The first simultaneous VHE $\gamma-$ray and optical polarization observations of PKS 2155–304 during an active state were recorded for Flare 2. A comparison between the fractional polarization and VHE flux shows that the increase in polarization degree precedes the rise in $\gamma-$ray flux by approximately one day. At radio to optical wavelengths the primary emission mechanism in blazars is synchrotron radiation, which produces polarized emission. VHE photons are produced by up-scattering the lower-energy synchrotron photons via the inverse Compton mechanism in a process known as synchrotron self-Compton (SSC) emission [12, 13, 14]. Since both processes are seeded by the same particle population correlations between fluctuations in the synchrotron and $\gamma-$ray emission are expected. It is therefore likely that the increase in the polarization degree and the gamma-ray flux are correlated and that the same evolving emission region is responsible for both.

3.2. A quasi-periodic oscillation in the intra-day polarization?

Inspection of the IDV on MJD = 55037, at the onset of the second $\gamma-$ray flare, suggests that the amplitude of the polarization degree is modulated on a timescale of $\sim$ 30 min, as illustrated in Fig. 2. These short-term amplitude modulations are superposed on a slowly decreasing baseline over the 290 minutes of continuous observation. It is noteworthy that such short-term modulations are not seen on MJD = 55038 and 55039. Since the most robust measurements were recorded in the $I-$band (higher signal-to-noise ratio compared to the $B-$band) we focus our analysis on the $I-$band polarization, which is represented by the Stokes Q and U fluxes.

To test for the presence of periodic components in the optical polarization we computed the Lomb-Scargle periodogram [15], which measures the amount of variability power as a function of temporal frequency (ν) relative to the variance (σ^2) of the observations. The periodogram of the de-trended Stokes Q and U polarized fluxes is displayed in Fig. 3. The Q periodogram reveals

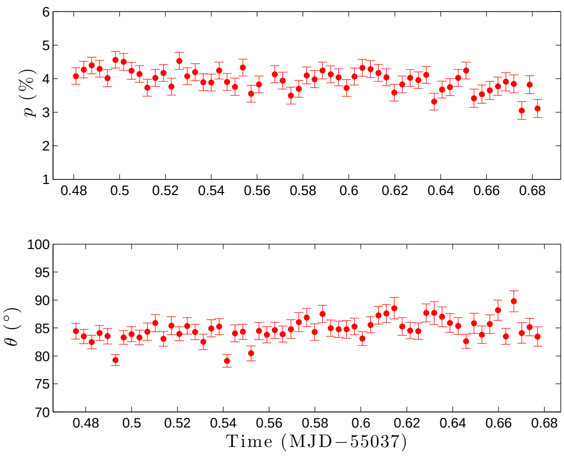

Figure 2. The intra-day variability of the I–band polarization of PKS 2155–304 as seen on 25 July 2009 (MJD = 55037). The top panel displays the polarization degree p (%), while the position angle of the electric vector θ (°) is shown in the bottom panel. The polarization degree appears to modulated by a periodic component at ∼30 minute intervals.

the presence of two dominant frequency components at $\nu = 563 \pm 10$ μHz and $\nu = 1293 \pm 9$ μHz. Each peak signal is well-described by a Gaussian function for which the errors are estimated from the full-width half-maximum and the peak height [16]. The amplitude of the Stokes Q flux therefore appears to be modulated by two periodic components, while no dominant peaks are detected in for U. The lack of detection in U is consistent with a variation in polarized intensity (as opposed to angle), as the observed polarization position angle $\theta \approx 90°$ (see Table 1 and Fig. 2), places virtually all the polarized emission in Q.

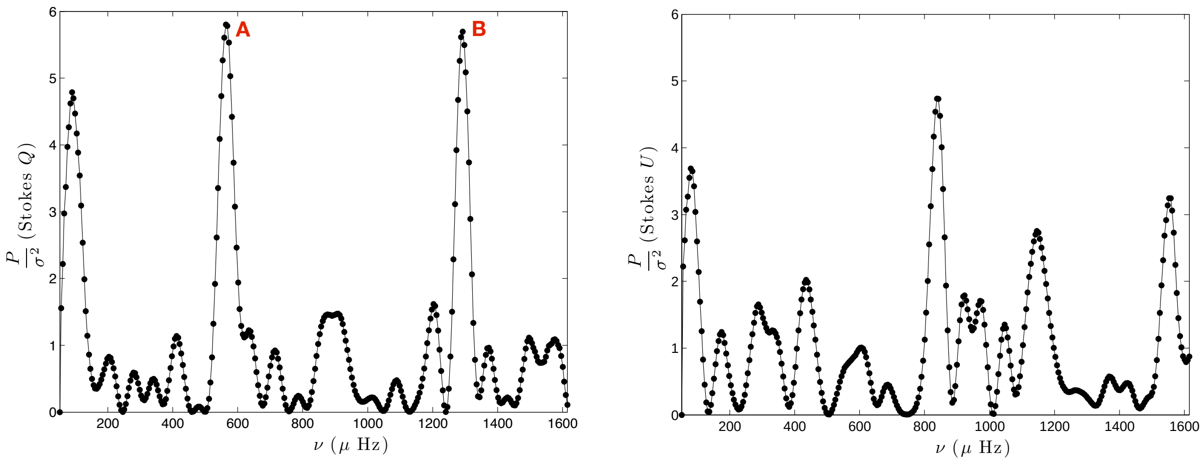

Figure 3. The periodogram of the Stokes Q and U polarized flux, shown in the left and right panel, respectively. Two prominent peaks are detected for Q at $\nu = 5.94 \times 10^{-4}$ Hz (corresponding to a period $T = 30$ min) and 12.9×10^{-4} Hz ($T = 13$ min), labelled as **A** and **B**, respectively. No dominant peaks are detected for U.

The phase-folded light curve of the Stokes Q flux is displayed in Fig. 4. Although the amplitude modulation is small, a cyclic trend appears to be present for both periods. A non-linear least-squares fit to the data yields a best-fit sinusoid that agrees well with the phase-folded diagram.

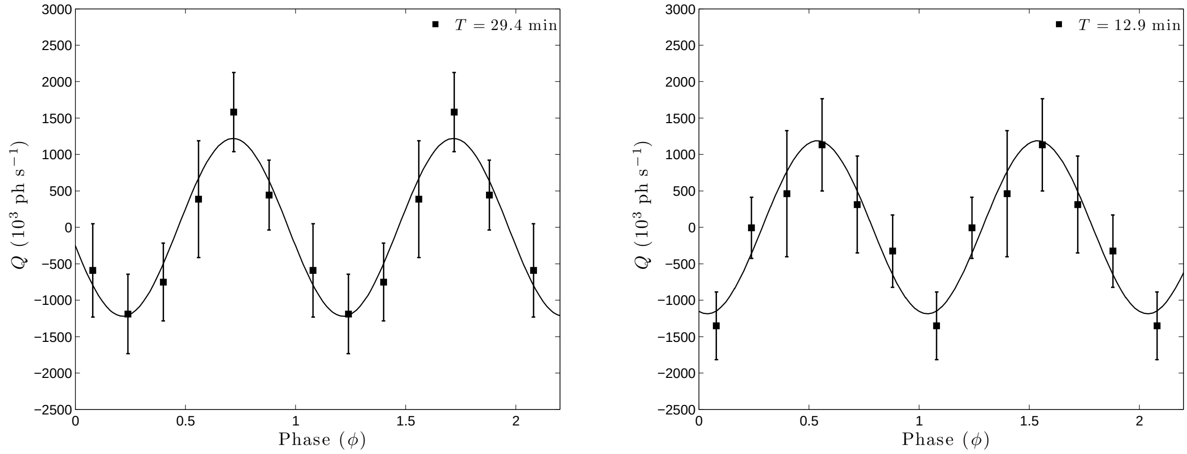

Figure 4. The phase-folded light curve of the Stokes Qflux, averaged in six phase bins, for $T = 30$ min and $T = 13$ min. Two cycles are plotted for clarity. A cyclic trend appears to be present for both periods. The solid line represents the best-fit sinusoid for each case.

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4. Discussion

Since blazar emission is dominated by radiation from the relativistic jet, any change in the direction of the emitted radiation with respect to the observer, even for small changes in the viewing angle, will give rise to brightness fluctuations due to Doppler boosting. Fast variations are typically attributed to shocks propagating down the jet [17, 18]. Quasi-periodic fluctuations can arise if the shock encounters helical structures in the jet, for example the magnetic field, electron density and or the jet flow. Then, successive peaks in the emitted flux will be observed every time the shock completes a turn. Turbulence behind the shock can also explain the presence of short-lived QPOs. For such turbulent flows, the largest eddies will dominate the variability and the period will be determined by their turnover times. Finally, it might also be possible to detect emission from orbital motions of rotating hot-spots near the accretion disk or corona of the central engine if the blazar is in a quiescent state. However, since optical polarization in blazars are the result of synchrotron radiation from the jet, the QPO observed in the polarized flux of PKS 2155–304 most likely originates in the jet.

5. Summary and Conclusions

Monitoring of the intra-day optical polarization of PKS 2155–304 revealed the first detection of QPOs in the polarized flux of an AGN. Two modulating components with periods of 30 min and 13 min were identified in the Stokes Q polarized flux. Overlapping gamma-ray observations of the source showed that it was in a high state of activity, experiencing two $\gamma-$ray flares. The first simultaneous optical polarization measurements of the source during a high-state was recorded for the latter flare. Although the physical cause of this QPO is unclear, comparison with the VHE light curve showed that the source experienced a $\gamma-$ray flare two days before the appearance of the QPOs and another peak two days later. The oscillations could therefore be related either to the late phase of post flare activity for the first flare or to the onset of the latter flare, which could suggest that the QPOs are part of a longer-lived phenomenon within the blazar jet.

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