The optical polarization of the blazar PKS 2155–304 during an optical flare in 2010 (Peceur et al. 2020, MNRAS 495, 2162)

N.W. Peceur[1], R. Taylor[123] and R.C. Kraan-Korteweg[1]

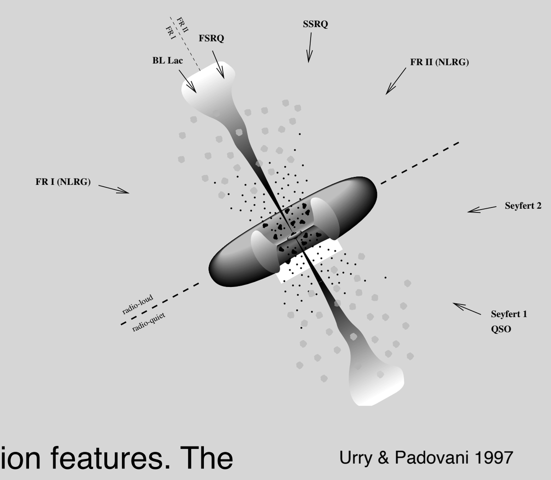
1. University of Cape Town 2. University of Western Cape 3. Inter-University Institute for Data Intensive Astronomy

ABSTRACT

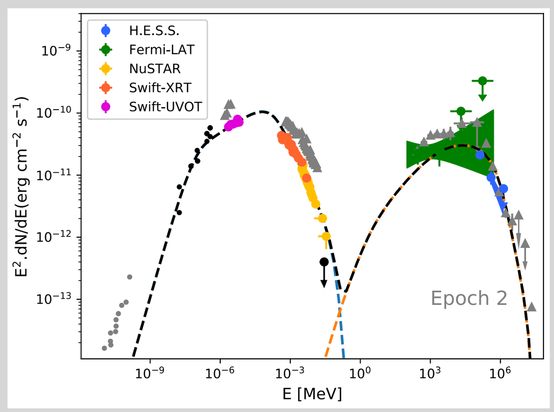
An analysis of the optical polarimetric and multi-color photometric (BVRJ) behaviour of the blazar PKS 2155-304 during an outburst in 2010 is presented. The flare develops over roughly 117 days and is associated with a flux doubling time of 11 days, which increases from blue to red wavelengths. The polarization angle is initially aligned with the jet axis but rotates by roughly 90 degrees as the flare grows. Two distinct states are evident at low and high fluxes. Below 18 mJy, the polarization angle takes on a wide range of values, without any clear relation to the flux. In contrast, there is a positive correlation between the polarization angle and flux above 18 mJy, with a correlation coefficient r = 0.84. The polarization degree does not display a clear correlation with the flux. We find that the photopolarimetric behaviour for the high flux state can be attributed to a variable component with a steady power-law spectral energy distribution and high optical polarization degree (13.3 %). These properties are interpreted within the shock-in-jet model, which shows that the observed variability can be explained by a shock that is seen nearly edge-on. Some parameters derived for the relativistic jet within the shock-in-jet model are the magnetic field strength, Doppler factor and viewing angle of the jet.

INTRODUCTION

Blazars are a subclass of radio-loud active galactic nuclei, where the relativistic jet is closely aligned to the line of sight of the observer (Urry & Padovani 1995) and for which the most extreme observational properties are detected (Aharonian et al. 2007). The observed radiation spans the entire electromagnetic spectrum, from radio to γ-ray wavelengths, and is dominated by non-thermal emission from a relativistic jet, as well as the presence of polarization at radio and optical wavelengths. The magnetic field of the jet therefore underlies the physical processes that produce the observed emission.



Urry & Padovani 1997



HESS 2020

The spectral energy distribution (SED) consists of two broad emission features. The low-energy peak is located at optical to soft X-ray energies and is due to synchrotron emission. The high-energy peak is located at hard X-ray to γ-ray energies and is attributed to Inverse Compton emission of the relativistic electrons (Aharonian et al. 2009, HESS 2020).

The polarization is a direct observable of the magnetic field and can provide useful information on the geometry and degree of order of the magnetic field of the jet. The polarization degree (PD) could be related to the level of ordering of the magnetic field or to the electron energy distribution within the emission region, while the position angle of the polarization (PA) could be related to the direction of the magnetic field along the line of sight.

POLARIZATION

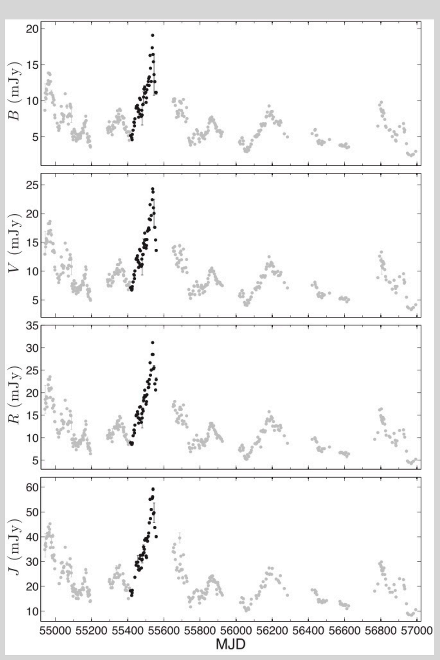
Various models have been proposed to explain the observed polarization of blazars. Here, we consider the polarization due to a large-scale helical magnetic field (Lyutikov et al. 2005), velocity shear (Laing 1980; D'Arcangelo et al. 2009), or the compression of an initially tangled magnetic field by shock waves in the jet (Marscher & Gear 1985; Cawthorne & Cobb 1990).

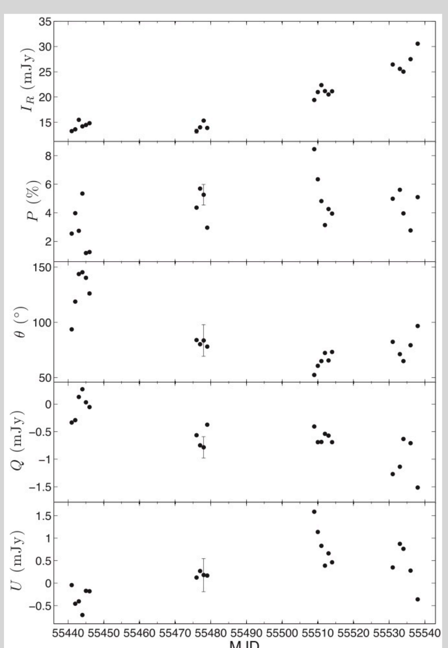
- **HELICAL MAGNETIC FIELD:** Net magnetic field (*B*-field) seen by the observer can appear to be either transverse or longitudinal
- **VELOCITY SHEAR:** Aligns the *B*-field of a turbulent magnetic field along the flow direction, leading to transverse PA
- **TRANSVERSE SHOCKS:** Partially orders a turbulent magnetic field by compressing the *B*-field component parallel to the shock front. The shock front is oriented transverse to the jet axis, resulting in PA aligned with the jet axis.
- **CONICAL SHOCKS:** PA can be either parallel or transverse to the jet axis. Largest possible PD for transverse PA is ~10 %.
- **TWO COMPONENT MODELS:** Polarization due to a variable component of higher PD plus a constant component with lower PD. Constant component identified with quiescent jet emission. Variable component attributed to shock.

OBJECTIVE

It is not clear which model best describes the photopolarimetric behaviour of flaring blazars. Here, we present quasi-simultaneous multiband photometric and polarization observations of the archetypal blazar PKS 2155–304 during a prominent optical flare in 2010, in an effort to understand the origin of the observed variability.

MULTIWAVELENGTH LIGHT CURVES





POLARIZATION: *R*-band polarization measurements from the Steward Observatory (SO)[1]

PHOTOMETRY: *B*, *V*, *R* & *J*-band measurements from Small and Moderate Aperture Research Telescope System (SMARTS)[2]

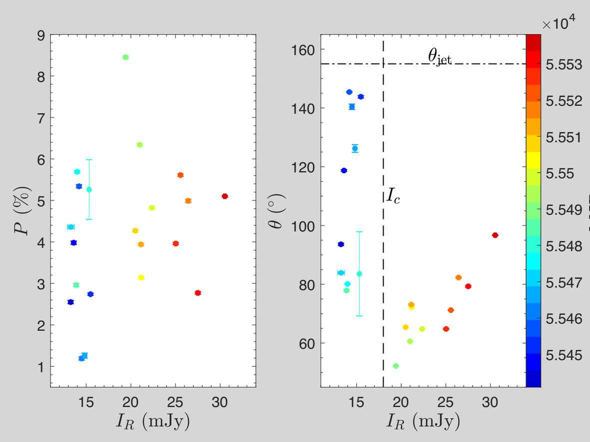
The resulting light curves between 2009 Apr and 2014 Dec are displayed on the leftmost figure and show:
- Presence of multiple flares
- Most prominent flare occurs in 2010

2010 FLARE

Simultaneous photopolarimetric measurements of PKS 2155–304 in 2010 (figure on the left) shows:
- Erratic variability for PD (*P*), while PA (*θ*) appears to follow an overall decreasing trend, changing by ~90°.
- At flare onset, PA is aligned with the jet (*θ* = 150°–160°; Piner et al. 2008, 2010), thereafter PA roughly transverse to the jet as flare grows.

TWO DISTINCT STATES?

Relationship between the *R*-band flux (I_R) and PD and PA is displayed on the right and shows:
- Existence of two distinct states at low and high flux for PA vs flux
- Below 18 mJy, *θ* takes on a range of values (~75°–150°) without any clear relation to the flux
- Above 18 mJy, a positive correlation is seen with r = 0.84 and
- PA oriented roughly transverse to the jet (60°–70°) for epoch of highest polarization.
- PD, in contrast, no clear correlation with flux, although maximum PD is detected during the high-flux state.



[1]The Steward Observatory archive can be found at http://james.as.arizona.e du/~psmith/Fermi/

[2]The SMARTS archive can be found at http://www.astr o.yale.edu/smarts/glast/home.php

VARIABLE EMISSION PARAMETERS

POLARIZATION AND SED PARAMETERS OF THE VARIABLE COMPONENT

Hagen-Thorn & Marchenko (1999) showed if the observed emission is decomposed as the superposition of a variable component and a constant component then if,

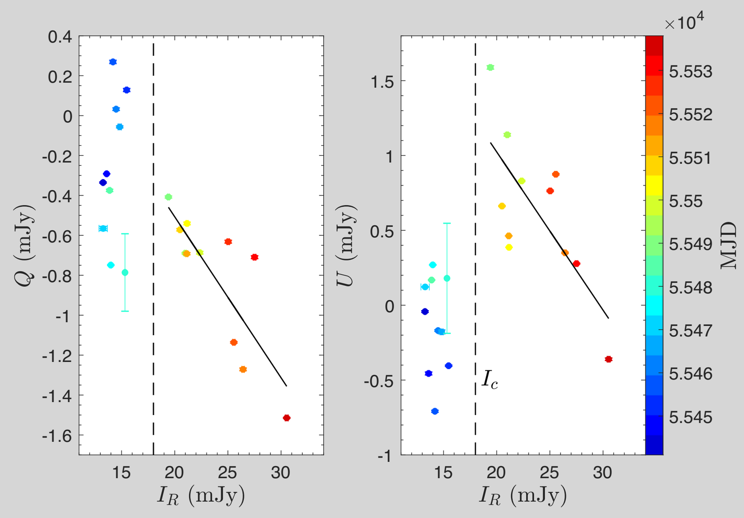
– The variable component has constant polarization properties

→ A linear relationship will be observed in the Stokes planes (*Q* vs *I* and *U* vs *I*)

and if,

– The relative SED of the variable component remains steady

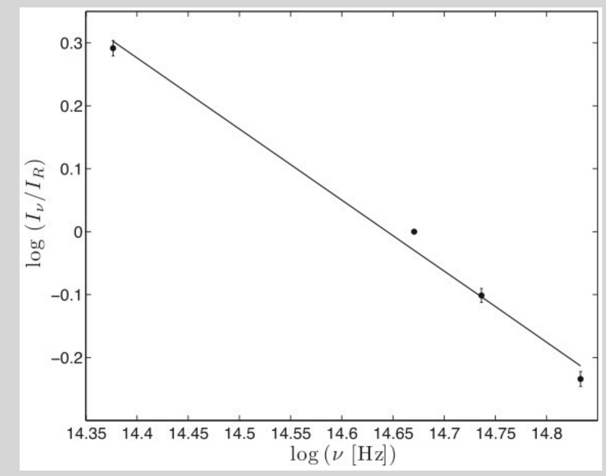
→ A linear relationship will be observed for the flux–flux diagrams for several bands



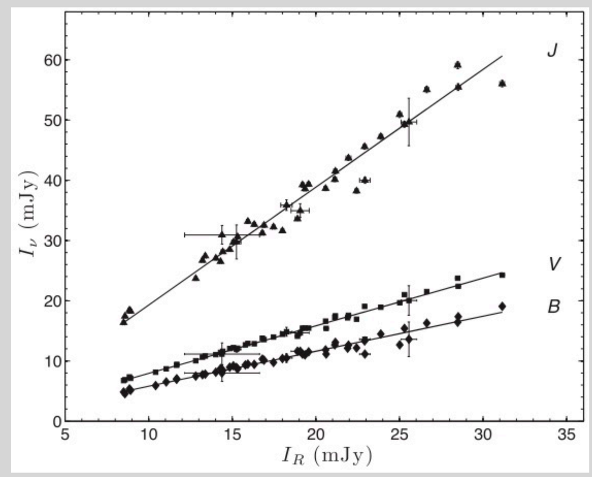
Absolute Stokes fluxes during 2010 optical flare of PKS 2155–304.The solid line gives the fit to the data for all *I* > 18mJy. The dashed line represents I_c = 18 mJy. Colour indicates the date of the observation, with the scale given by the colour bar.

STOKES PARAMETERS:
- For I_R > 18 mJy: *Q* ∝ *I* and *U* ∝ *I*, with r_{Q-I} = –0.82 and r_{U-I} = –0.72 (shown on the left)
- Slope of each line gives relative Stokes parameters of variable component

→ P_{var} **= 13.3 ± 2.8 % and** θ_{var} **= 116° ± 6**



Relative SED of the variable emission component of PKS 2155– 304 during its 2010 outburst. The best fit line is superimposed, with slope α = 1.12 ± 0.07.

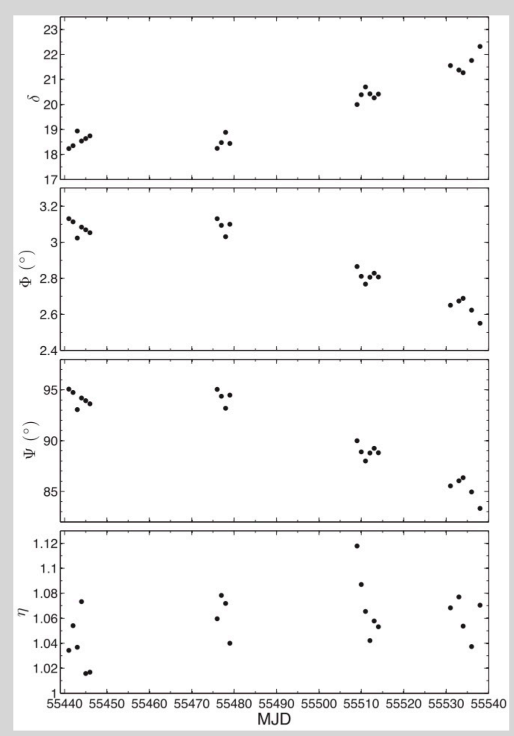


The *B*-, *V*- and *J*-band fluxes relative to the *R*-band flux during the 2010 optical flare of PKS 2155–304. The best-fit lines are superimposed.

FLUX–FLUX DIAGRAMS:
- Linear relationship seen in flux–flux diagrams displayed on the left
- Slopes of best-fit lines give flux ratio (I_ν / I_R) between the given pairs of bands

→ **Relative SED (displayed above) well described by power-law with slope** ***α*** **= 1.12 ± 0.07, consistent with synchrotron emission**

SHOCK-IN-JET MODEL



Derived values for the Doppler factor *δ*, jet viewing angle *Φ*, viewing angle of the shock *ψ*, and compression factor of the shocked plasma *η* for PKS 2155–304 for the 2010 flare.

Observed flux of shock moving through turbulent plasma with constant bulk Lorentz factor Γ:

$$F = F_0 \nu^{-\alpha} \delta^{(3+\alpha)} \delta'^{(2+\alpha)},$$

where *F* is the flux scaling factor, *δ* is the Doppler factor of the jet in the observer's frame, and the PD for a shocked plasma (Hughes & Miller 1991):

$$p \approx \frac{\alpha+1}{\alpha+5/3} \frac{(1-\eta^{-2})\sin^2\psi}{2-(1-\eta^{-2})\sin^2\psi},$$

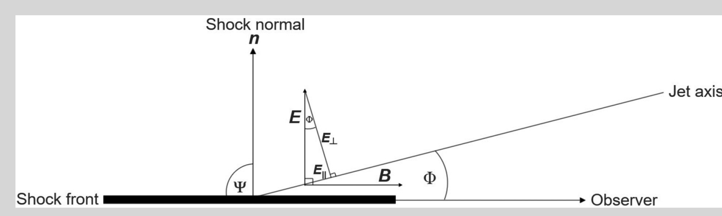
where $\eta = n_{shock}/n_{unshocked}$ is the density of the shocked region relative to the unshocked region and *ψ* is the viewing angle of the shock in the observer's frame. The evolution of the shock parameters are derived by adopting α = 1.12 (spectral index of the variable component) and Γ ~ 20 (Foschini et al. 2007; Reynoso et al. 2012).

The results are displayed on the left and show that:
- Small changes in jet's viewing angle (Φ < 1°) and plasma compression (*η* = 0.10) produce large variations in flux and PD
- Peak flux is reached when the **viewing angle of the jet** is minimum **(Φ = 2.6°)**
- **Max** ***δ*** **= 22.3**
- No systematic trends for the plasma compression *η*
- Shock is seen nearly edge-on throughout flare (*ψ* ~ 91°), varying by <12°

→ **Implies that shock is seen at oblique angle to jet axis (see figure below)**

Compression of the magnetic field by the shock yields a net *B*-field parallel to the shock front yielding electric field (*E*-field) components $E_\perp \approx E$ and $E_\parallel \approx 0$ for the small angle approximation.

→ PA for edge-on shock is expected to lie transverse to the jet axis. Observations during peak polarization epoch is consistent with this, with *θ* ~ 60°–70°.



Electric field from shock compression of a tangled magnetic field for edge-on shock (ψ = 90°) for a blazar with viewing angle Φ

MAGNETIC FIELD

For shock-in-jet, the variability timescale relates to the thickness of the shock front, which is determined by the lifetime of the relativistic electrons accelerated at the front. The lifetime of synchrotron electrons for a given frequency *ν* in the observer's frame is (Hagen-Thorn et al. 2008):

$$t_{sync} = 4.75 \times 10^2 \left(\frac{1+z}{\delta \nu_{GHz} B_G^3}\right)^{1/2} \text{d},$$

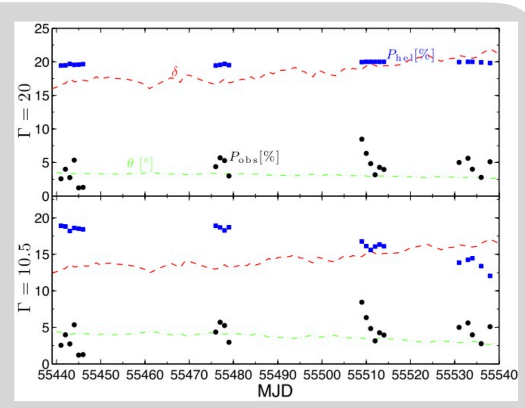
, where B_G is the magnetic field in Gauss and *z* is the redshift. Adopting the maximum derived Doppler factor for the observations (*δ* = 22.3) and *τ* = 10.75 d in the *R*-band yields ***B*** **= 0.06 G**.

HELICAL MAGNETIC FIELD MODEL

The observed polarization for a jet pervaded by a helical magnetic field is (Lyutikov et al. 2005):

$$P = P_{max} \sin^2 \phi$$

, with $P_{max} \approx 20$ % and *ϕ* the viewing angle in jet's rest frame (related to observed angle through sin*ϕ* = *δ* sinΦ). Doppler factor is obtained from the observed flux due to a relativistic plasma for a smooth, continuous jet $F_\nu = \delta^{2+\alpha} F_\nu'$, where F_ν' denotes the flux in the jet's rest frame. The results show (see figure on the right):
- The helical magnetic field model overestimates the observed PD
- Unlikely that the observed polarization of PKS 2155–304 during the 2010 flare is due to a helical magnetic field.



Doppler factor *δ* (red) and viewing angle *θ* (green) for the optical flux variability for bulk Lorentz factor Γ = 20 & 10.5. The polarization degree for the helical magnetic field model is shown in blue, while the observations are shown in black.

CONCLUSIONS

PKS 2155–304 experienced a prominent optical flare in 2010, increasing by a factor of 3.7 over ~4 months. The multicolour photometric measurements and *R*-band polarization indicate:

1. The existence of two distinct states at low and high fluxes
2. During the high-flux state, the PA at the epoch of highest polarization tends to be oriented transverse to the jet
3. The variable emission can be explained by a single variable component with PD = 13.3 % and a constant power-law SED with *α* = 1.12 ± 0.07

These properties are consistent with the shock-in-jet model, which shows that the observed variability can be explained by an edge-on shock. Some parameters derived for the relativistic jet within the shock-in- jet model are ***B*** **= 0.06 G for the magnetic field,** ***δ*** **= 22.3 for the Doppler factor, and Φ = 2.6° for the viewing angle.**