Optical Outburst of the blazar S4 0954+658 in early 2015

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We analyze the behavior of the BL Lac object S4 0954+658 during an unprecedented bright optical flare in early 2015. The optical flare was accompanied by a powerful γ-ray flare and detection of VHE-emission (ATel #7080). We analyze total and polarized intensity images obtained with the VLBA at 43 GHz and discover a new bright polarized superluminal knot, which passed through the VLBI-core during the peak of the flare. Such a close connection between these events in different wavebands supports the conclusion that optical and γ-ray emission are produced in a region located in the vicinity of the mm-wave core of the jet.

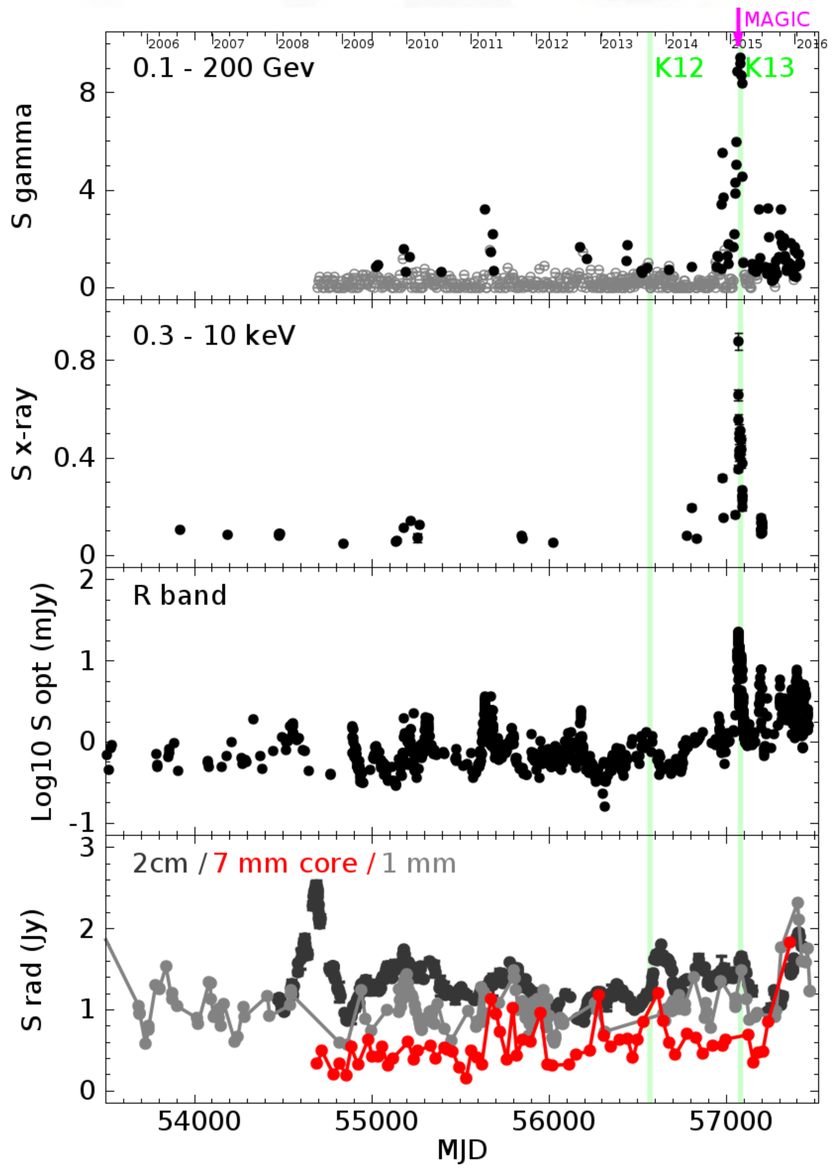


Fig.1 Light curves of S4 0954+658 from 2005 to 2016 (from top to bottom): γ-ray, x-ray, R-band optical, and radio (1mm, 7mm, and 2cm) data.

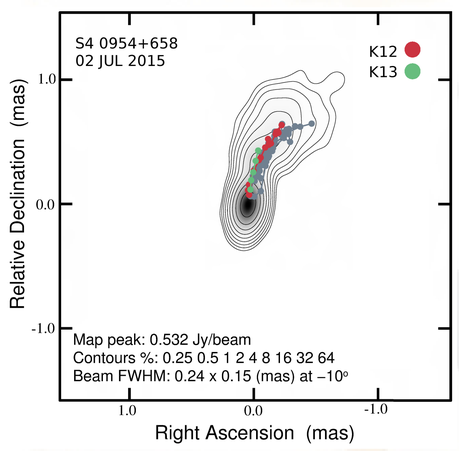


Fig.2 43 GHz image of S4 0954+658 with trajectories of knots superposed. Components ejected during 2006-2014 are marked in gray

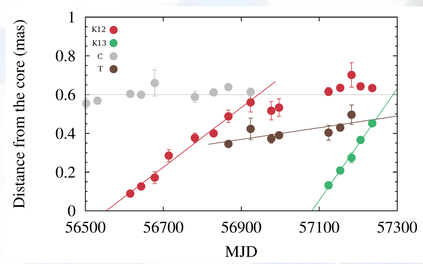


Fig.3 Separations of knots from the VLBI-core as a function of time at 43 GHz.

1. Introduction

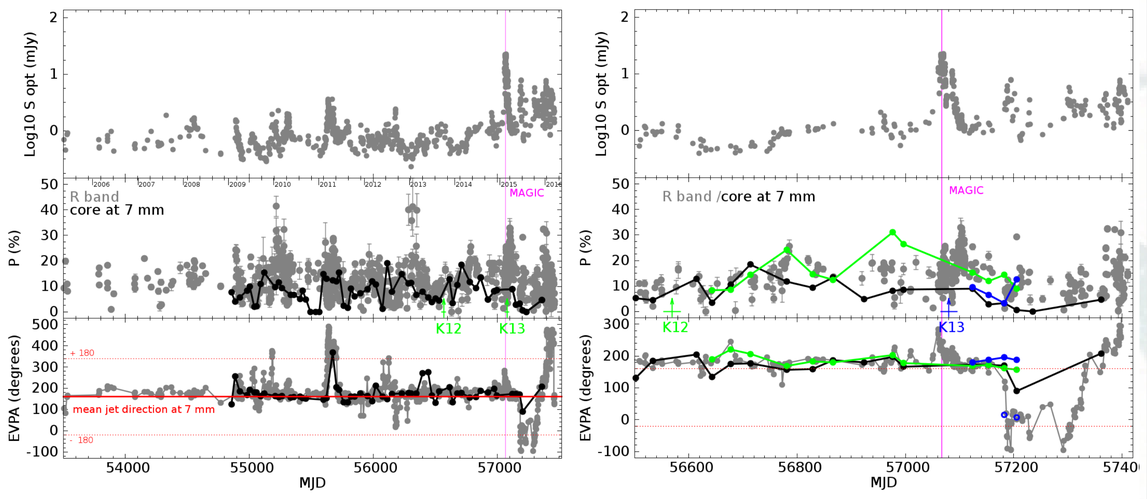
The blazar S4 0954+658 (z=0.367) is a well-studied BL Lac object at optical wavelengths. It displays significant flux and polarization variability on both intraday and longer timescales.

2. Observations and data reduction

We obtain optical (R-band) flux densities from photometric observations at the 0.4 m telescope of St. Petersburg State U. (LX200) and 0.7 m telescope of the Crimean Astrophysical Observatory (AZT-8). The data analysis for these telescopes is described in Hagen-Thorn et al 2006. We also use R-band data obtained with the Perkins Telescope*.

We derive 0.1-200 GeV γ-ray flux densities by analyzing data from the Large Area Telescope (LAT) of the Fermi γ-ray Space Telescope with the standard software (Abdo et al. 2009). We have constructed γ-ray light curves with 7-day binning, with a detection criterion that the maximum-likelihood test statistic (TS) should exceed 10.0. We also include Swift/XRT automatically processed data** (Stroh & Falcone 2013).

The BL Lac object S4 0954+658 is monitored monthly by the BU group with the VLBA at 43 GHz within a sample of bright γ-ray blazars*. We analyze total and polarized intensity images produced by the BU group and collaborators. Each image in Stokes I, Q, and U parameters was fit by a model consisting of a number of components with circular Gaussian brightness distributions. Identification of components in the jet across epochs is based on analysis of their flux, position angle, distance from the core, size, degree of polarization, and EVPA. We have computed kinematic parameters of knots (proper motion, velocity, and acceleration) by fitting the positions of each component over epochs by different polynomials, in the same manner as described in Jorstad et al. (2005). In addition, we use data from OVRO (Richards et al. 2011) and SMA monitoring programs to construct radio band light curves.



a b

Fig.4 (from top to bottom): the R-band optical light curve, fractional polarization, and EVPA. **a:** Gray dots show measurements in R band, black dots are those of the VLBI-core at 43 GHz. **b:** Green and blue dots correspond to knots K12 and **K13, respectively.**

3. Results and Discussion

In early 2015 S4 0954+658 underwent a dramatic outburst at all wavelengths from γ to radio band. Fig.1 presents the light curves of the source at different wavelengths during 2006-2016.

The flare in 2015 February-March was the brightest optical state ever observed for the blazar. High-amplitude intra-night variations were detected in both optical light and fractional polarization. Two noticeable episodes of fast variability were observed on February 11 (MJD=57064.68), when the flux varied by 0.24 mag in 1.92 hours and 0.4 mag in 6.0 hours, while the fractional polarization varied from 9.4% to 16.7%. An episode of spectacular variability occurred on March 4 (MJD=57085.71), including a 0.23 mag flux increase in 2.1 hours, and 0.57 mag smooth decline 6.48 hours later, while the fractional polarization varied from 3 to 15 %. It should be noted that violent intra-night variability (~0.7 mag in 7 hours and ~1.0 mag in 5 hours) was previously observed during the prominent outburst in March-April 2011 (see Morozova et al. 2014) as well.

Although the γ-ray flux falls below the detection limit during most of the period of Fermi observations, the source exhibits the highest γ-ray activity and shows substantial variability during the 2015 flare. According to the Swift data, there is a bright x-ray flare contemporaneous with the γ-ray flare. In addition to the prominent GeV γ-ray activity, VHE emission was detected by MAGIC (Atel #7080) on 13-14 February 2015 (MJD = 57067).

The flux of the 43 GHz VLBI-core, as well as the polarization degree, increased just before and after the optical flare maximum. Unfortunately, we have no VLBA data at 43 GHz during the flare maximum. Because of this, we cannot determine directly whether the core was in a high state, but the optical flare was contemporaneous with flares at 1 mm and 2 cm, which most likely originated in the core. One can see in Fig.1 that the VLBI-core light curve is in agreement with the flux variations at 1 mm and 2 cm during the whole span of the observations. The pattern of the flux variations in radio and optical bands is quite similar, although the radio light curve is smoother.

We carefully study the optical and radio polarization behavior of S4 0954+658 near the ejection times of the components. At the quiescent state the optical EVPA is quite stable (~ -10°) and tends to align with the parsec-sale jet direction at 43 GHz (~ -20°). Fig. 4 shows that the optical EVPA is also in good agreement with the EVPA of the core. The fractional polarization of the core usually increases during optical activity (see Morozova et al. 2014).

During 2015, several components can be seen in the jet at 43 GHz: K12,K13, C, T (see Morozova et. al 2014 for the analysis of the jet kinematics during 2006-2012). Knot K12 was ejected at ~ MJD 56670 (βapp = 12.9±0.23, P.A.= 13°±8). Knot C is a stationary component, and the knot T is most likely a trailing component generated by K12.

The polarization parameters of K12 (EVPA and polarization degree) are similar to the optical polarization parameters at several epochs after its ejection from the 43 GHz VLBI-core (see Fig.4 b). The knot maintained a high level of fractional polarization during later epochs.

The ejection of knot K13 (MJD 57080±15) is contemporaneous with the optical flare in early 2015 (see Fig.1,Fig.4 a,b). The apparent velocity of the knot (βapp=23.8±0.5) is higher than that of previous components, and the P.A. (-7±2°) is quite different from the mean direction of previously ejected components (~ -15° to -25°, see Morozova et al.2014). The EVPA of K13 is also close to the optical value, but, due to gaps in time coverage of the VLBA data, it is difficult to resolve the 180° uncertainty at MJD ~ 57200 (see Fig. 4b).

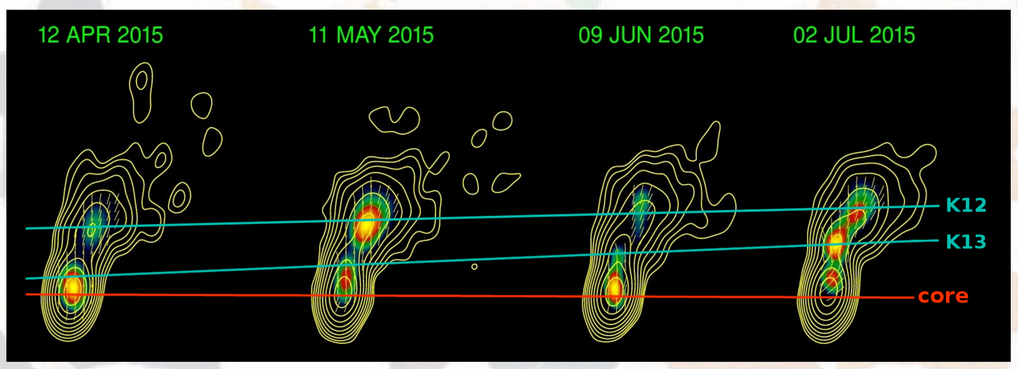


Fig. 5 Total (yellow contours) and polarized (color scale) intensity images at 43 GHz; yellow line segments over the color scale show the direction of the electric vector.

4. Conclusions

In early 2015 the blazar S4 0954+658 underwent a dramatic outburst at all wavelengths and VHE emission was detected by MAGIC (Atel #7080). During the maximum of the flare, a highly polarized component, K13 was ejected from the VLBA-core at 43 GHz. These results confirm the connection between the jet behavior at 43 GHz and activity at higher energies which was inferred from previous observations of S4 0954+658 (Morozova et al. 2014). The presence of such a connection implies that the multi-wavelength flare in early 2015 occurred near the 43 GHz VLBA-core.

References

Abdo, A.A., Ackermann, M., Ajello, M., et al. 2010, 188, 405
Hagen-Thorn,V.A., Larionov, V.M.,et al., 2006, Astr. Rep. 50, 458
Jorstad, S. G., Marscher, A.P., Lister, M.L., et al. 2005, AJ, 130, 1418
Morozova, D. A., Larionov, V. M., Troitsky, I. S., et al. 2014, AJ, 148, 42
Richards, J. L. et al. 2011, ApJS, 194, 29
M.C. Stroh & A.D. Falcone 2013, ApJS, 207, 28

* http://www.bu.edu/blazars

**http://www.swift.psu.edu/monitoring/

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Acknowledgments

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