Photometric Benchmarks of Bright Blazars in the Northern Hemisphere

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BL Lacertae objects: general; galaxies: photometry; quasars: general

1. Introduction

To better understand AGN flaring rates and magnitudes, we observed 192 bright northern blazars from 2015 August to 2016 July. We obtained statistically relevant data on 161 of these and publish their Johnson *B* and *R* magnitudes here. Thirteen objects, about 4% of our sample, varied in one of two modes, stochastic or smooth. One object, AO 0235+164, brightened by 1.5 mag in 10 days and dimmed to its previous magnitude within two months.

Blazars are noted for sudden and often dramatic variability. This variability may be caused by particle injection, acceleration and cooling within the jet, shock waves, turbulence, or changes in the viewing angle of the observed emitting knots or jet regions (see Raiteri et al. 2017). In addition to stochastic variability, some blazars have been reported to exhibit smoother, more regular variations as well (i.e., Charisi et al. 2016).

Bright blazars, particularly those with high energy and frequent outbursts, are monitored by the "Whole Earth Blazar Telescope" or "WEBT" (Villata et al. 2002). A participant telescope in this system is the 0.4 m Remote Observatory for Variable Object Research (ROVOR) telescope owned by BYU (Moody et al. 2012).

Beginning in the summer of 2015 we used ROVOR for a year-long monitoring campaign designed to determine the current stability of the brightest 192 blazars in the northern hemisphere. The candidate objects were chosen from the American Ephemeris, the Veron Cetty–Veron AGN catalog (Veron-Cetty & Veron 2010), and the WEBT list of high-energy blazars. Each object included had a cataloged visual magnitude brighter than 16.0 and a decl. greater than 0 degrees. Blazar brightnesses vary, and in reality many were fainter than this limit. Remarkably, only about 10 per of the blazars observed here have been monitored regularly since their discoveries.

2. Observation

Each object was observed as frequently as weather would permit between 2015 August and 2016 July. All were observed on at least three different nights with some being observed on as many as 22 different nights. All observations were taken with the 0.4 m ROVOR telescope operating in robotic mode. Each nightly observation consisted of 11 60 s observations; 6 in Johnson *V* and 5 in Johnson *R*.

3. Analytical Techniques

Photometry was done using the *MIRA* software package. Calibration to the Johnson system was done using 11 in-field secondary standard stars in each field. All secondary standard stars were calibrated by us on photometric nights using standards from Landolt (2009). Such "all-sky" calibrations were conducted 1–12 times on each field, with an average of four times per field, in accordance with the procedures laid out in Pace et al. (2013).

We flagged each blazar as varying if the magnitude variations were twice that of the color uncertainty. This is expressed in Equation (1) as

$$\frac{\sigma_v}{\sigma_{v-r}} \geqslant 2 \text{ and } \frac{\sigma_r}{\sigma_{v-r}} \geqslant 2 \qquad (1)$$

where σ_v, σ_r, and σ_{v-r} are the standard deviations in our observed *V* magnitudes, *R* magnitudes, and $V - R$ values respectively. In other words, we assumed the $V - R$ color term to be constant with time meaning its variation estimates photometric error. The ratio of the standard deviation in the *V* and *R* magnitudes to the standard deviation in $V - R$ being greater than 2 means the intrinsic variability was essentially two sigmas greater than the scatter.

We identified two distinct groups of variability; "smooth" and "stochastic." We fit each blazar light curve with a third order polynomial and considered it as smooth if the *R*-squared value of the fit was 0.7 or greater and as stochastic if less. There is a distinct bimodal distribution. The variable blazars either had low or high values of *R*-squared, none were intermediate.

4. Data

Of the 192 objects from our original list, 161 had sufficient data to be analyzed in the manner described above. We present the results in Table 1. Column 1 is the object name. Columns 2–3 give the *V* magnitudes and standard deviation. Column 4 presents the difference between the minimum and maximum observed magnitudes in *V*. Columns 5–7 present the same information for the *R* band. Of the blazars marked as variable, we found median Min–Max values of 0.60 and 0.55 for *V* and *R* respectively. Column 8 lists the type of confirmed variability. Ellipses dots mean we could not confirm variability at the 2-sigma level. Column 9 gives the number of nights each object was observed.

Table 1. Photometry of the 161 Objects with Reliable Data

Name	Avg *V*	Std Dev	Min–Max	Avg *R*	Std Dev	Min–Max	Variability	Nights

Name	Avg V	Std Dev	Min–Max	Avg R	Std Dev	Min–Max	Variability	Nights
4C 25.01	16.05	0.07	0.27	15.75	0.05	0.19	⋯	13
A 0021+25	15.71	0.05	0.19	15.04	0.04	0.17	⋯	18
PG 0026+129	15.43	0.07	0.25	15.14	0.04	0.15	⋯	16
PB 6151	16.19	0.10	0.35	15.82	0.06	0.22	⋯	14
MK 1148	15.52	0.22	1.04	15.13	0.19	0.92	Stochastic	16
1ZW 1	14.16	0.05	0.24	13.71	0.04	0.16	⋯	16
PG 0052+251	15.31	0.10	0.45	15.09	0.08	0.31	⋯	18
PHL 909	16.24	0.08	0.30	15.87	0.03	0.12	⋯	14
IRAS 01072-0348	15.80	0.07	0.24	15.47	0.06	0.26	⋯	10
GC 0109+224	15.14	0.15	0.49	14.70	0.14	0.45	⋯	14
MK 357	15.34	0.07	0.26	15.16	0.04	0.15	⋯	12
1ES 0120+340	17.47	0.16	0.54	16.61	0.07	0.21	⋯	10
IRAS 01475+3554	16.50	0.12	0.49	15.96	0.09	0.31	⋯	14
MK 1014	15.74	0.11	0.44	15.40	0.06	0.23	⋯	10
MK 586	15.60	0.09	0.37	15.39	0.05	0.14	⋯	10
3C 59	16.79	0.12	0.49	16.24	0.06	0.21	⋯	12
PKS 0215+015	18.30	0.32	0.78	19.32	1.46	3.37	⋯	3
B3 0225+389	18.83	0.54	1.66	17.86	0.41	1.48	⋯	13
1ES 0229+200	16.88	0.13	0.46	16.14	0.12	0.43	⋯	12
AO 0235+164	18.41	0.60	2.22	17.50	0.59	2.12	Stochastic	9
S2 0241+62	16.75	0.11	0.44	15.66	0.09	0.31	⋯	10

Name	Avg V	Std Dev	Min–Max	Avg R	Std Dev	Min–Max	Variability	Nights
4U 0241+61	16.86	0.12	0.53	15.69	0.07	0.24	⋯	13
3C 84	13.12	0.05	0.17	12.52	0.05	0.20	Smooth	12
3C 110	17.39	0.11	0.22	17.27	0.35	0.70	⋯	2
MG 0509+0541	15.62	0.28	0.96	15.18	0.25	0.94	⋯	12
HS 0624+6907	14.43	0.03	0.12	14.09	0.03	0.11	⋯	9
1ES 0647+250	15.84	0.16	0.48	15.45	0.16	0.44	⋯	9
MS 07007+6338	15.58	0.03	0.12	15.33	0.03	0.08	⋯	10
7ZW 118	15.37	0.09	0.35	14.92	0.05	0.16	⋯	11
B2 0709+370	15.70	0.06	0.16	15.48	0.05	0.14	⋯	10
4C 41.30	15.68	0.05	0.13	15.54	0.04	0.13	⋯	10
OI+90.4	17.21	0.18	0.58	16.57	0.10	0.33	⋯	9
1E0754+39.4	14.65	0.07	0.27	14.37	0.05	0.20	⋯	10
IRAS 07598+6508	14.67	0.02	0.06	14.45	0.02	0.06	⋯	9
1ES 0806+524	15.35	0.07	0.19	14.90	0.07	0.20	⋯	8
PG 0804+761	14.69	0.12	0.46	14.46	0.10	0.38	⋯	11
US 1329	15.58	0.13	0.49	15.30	0.05	0.18	⋯	10
CSO 199	16.81	0.09	0.27	16.51	0.08	0.26	⋯	7
7ZW 244	16.26	0.09	0.33	15.94	0.03	0.10	⋯	7
SBS 0909+532	16.52	0.07	0.22	15.90	0.04	0.12	⋯	6
TON 1057	15.39	0.10	0.32	15.06	0.11	0.38	⋯	7
TON 1078	16.37	0.06	0.17	16.13	0.03	0.09	⋯	6

Name	Avg *V*	Std Dev	Min–Max	Avg *R*	Std Dev	Min–Max	Variability	Nights
4C 12.35	18.69	0.47	1.23	18.53	0.10	0.24	···	4
3C 232	15.82	0.09	0.25	15.52	0.04	0.11	···	5
MK 132	16.23	0.07	0.19	15.93	0.07	0.21	···	5
4C 13.41	15.61	0.03	0.06	15.25	0.02	0.05	···	2
TON 488	17.01	0.12	0.40	16.63	0.15	0.47	···	7
TON 1187	15.98	0.17	0.46	15.55	0.06	0.17	···	5
SBS 1010+535	16.44	0.16	0.50	16.15	0.09	0.31	···	8
TON 34	16.39	0.06	0.16	16.01	0.09	0.24	···	4
B3 1019+397	17.11	0.19	0.67	16.79	0.10	0.31	···	8
MK 142	15.70	0.18	0.50	15.22	0.06	0.16	···	4
SBS 1047+550	16.93	0.18	0.57	16.85	0.10	0.31	···	6
RX J10547+4831	16.12	0.11	0.30	15.79	0.09	0.35	···	8
TON 52	16.63	0.17	0.47	16.39	0.05	0.13	···	4
3C 249.1	15.52	0.04	0.13	15.21	0.03	0.09	···	6
MK 421	13.14	0.22	0.68	12.71	0.19	0.55	Smooth	13
HS 1103+6416	15.87	0.10	0.28	15.43	0.08	0.24	···	5
4C 16.30	16.75	0.02	0.05	17.00	0.32	0.64	···	2
TON 1388	15.01	0.03	0.06	14.76	0.02	0.06	···	3
SBSG1116+518	17.36	0.23	0.66	17.08	0.16	0.52	···	6
TON 580	16.67	0.09	0.25	16.36	0.03	0.08	···	4
MK 180	14.68	0.09	0.26	14.14	0.07	0.23	···	6

Name	Avg V	Std Dev	Min–Max	Avg R	Std Dev	Min–Max	Variability	Nights
RX J11479+2715	16.42	0.08	0.22	16.11	0.09	0.23	⋯	4
CBS 147	17.93	0.23	0.69	17.51	0.11	0.32	⋯	6
OM+280	16.70	0.10	0.23	16.18	0.18	0.44	⋯	3
PG 1151+118	16.30	0.03	0.08	16.01	0.02	0.05	⋯	3
TON 599	17.03	0.15	0.44	16.63	0.18	0.53	⋯	6
GQ Com	16.66	0.13	0.29	16.25	0.07	0.17	⋯	3
PG 1206+459	15.58	0.12	0.30	15.35	0.03	0.09	⋯	4
PG 1211+143	14.78	0.10	0.30	14.56	0.05	0.15	⋯	5
1ES 1212+078	16.85	0.12	0.24	16.12	0.08	0.16	⋯	2
ON+325	14.90	0.05	0.14	14.48	0.06	0.15	⋯	4
RS 4	16.49	0.00	0.01	16.03	0.05	0.12	⋯	3
MK 205	15.53	0.38	1.10	14.86	0.04	0.13	⋯	6
TON 618	15.99	0.02	0.06	15.68	0.04	0.09	⋯	3
3C 273.0	13.12	0.03	0.06	12.91	0.01	0.02	⋯	3
RX J12302+2517	16.00	0.23	0.65	15.64	0.28	0.81	Smooth	5
TON 1542	15.07	0.05	0.13	14.60	0.03	0.08	⋯	4
TON 83	16.77	0.03	0.08	16.48	0.03	0.08	⋯	4
CSO 151	17.13	0.26	0.78	16.63	0.07	0.22	⋯	6
SBS 1234+607	18.37	0.43	0.96	17.86	0.09	0.23	⋯	3
PG 1241+176	16.33	0.02	0.06	15.94	0.01	0.03	⋯	4
PG 1246+586	16.33	0.09	0.27	15.92	0.07	0.20	⋯	6

Name	Avg V	Std Dev	Min–Max	Avg R	Std Dev	Min–Max	Variability	Nights
LB 19	15.71	0.04	0.10	15.37	0.03	0.06	⋯	3
KUV 12491+2932	16.23	0.07	0.16	15.96	0.02	0.04	⋯	3
Q 1252+0200	16.29	0.11	0.35	16.03	0.09	0.25	⋯	6
1ES 1255+244	17.29	0.18	0.44	16.73	0.12	0.29	⋯	3
LB 2522	15.72	0.09	0.21	15.28	0.07	0.19	⋯	4
PG 1307+086	16.09	0.12	0.38	15.76	0.08	0.26	⋯	6
TON 1565	15.53	0.05	0.13	15.24	0.04	0.10	⋯	4
TON 153	15.97	0.10	0.30	15.77	0.08	0.23	⋯	6
PG 1322+659	15.66	0.03	0.08	15.42	0.02	0.05	⋯	3
4C 55.27	18.20	0.39	1.04	18.02	0.30	0.78	⋯	4
TON 730	15.95	0.09	0.29	15.59	0.08	0.25	⋯	6
MK 662	15.51	0.09	0.28	15.08	0.10	0.32	⋯	6
PB 4142	16.36	0.13	0.28	15.99	0.09	0.22	⋯	3
TON 182	16.10	0.13	0.34	15.81	0.12	0.35	⋯	5
PG 1404+226	15.98	0.04	0.10	15.67	0.05	0.15	⋯	4
PG 1407+265	15.88	0.10	0.32	15.81	0.09	0.28	⋯	6
PG 1411+442	14.94	0.08	0.22	14.63	0.07	0.21	⋯	4
PG 1415+451	15.90	0.08	0.20	15.51	0.06	0.15	⋯	4
1E 1415+259	17.08	0.18	0.47	16.53	0.04	0.10	⋯	4
OQ+530	15.67	0.22	0.61	15.13	0.22	0.59	Smooth	5
KUV 14207+2308	16.01	0.06	0.16	15.65	0.06	0.16	⋯	4

Name	Avg V	Std Dev	Min–Max	Avg R	Std Dev	Min–Max	Variability	Nights
2E 1423+2008	16.84	0.20	0.51	16.39	0.07	0.16	⋯	4
PKS 1424+240	14.76	0.12	0.37	14.36	0.19	0.56	Smooth	6
MK 813	14.98	0.04	0.12	14.70	0.06	0.14	⋯	4
TON 202	16.83	0.15	0.38	16.56	0.11	0.34	⋯	5
MK 1383	14.54	0.05	0.15	14.21	0.06	0.15	⋯	4
PG 1437+398	16.94	0.07	0.20	16.42	0.05	0.15	⋯	6
MARK 478	14.71	0.08	0.22	14.36	0.04	0.11	⋯	4
PG 1444+407	16.07	0.07	0.21	15.75	0.05	0.13	⋯	5
MK 830	17.31	0.08	0.23	16.78	0.09	0.27	⋯	6
MK 840	16.51	0.27	0.71	15.90	0.10	0.27	⋯	5
1H 1515+660	17.09	0.28	0.86	16.82	0.26	0.87	⋯	7
MCG+11-19-005	15.73	0.03	0.08	15.09	0.03	0.09	⋯	5
RX J15291+5616	16.59	0.54	1.60	16.35	0.51	1.40	⋯	6
PG 1538+478	16.05	0.06	0.17	15.82	0.04	0.11	⋯	5
1ES 1544+820	17.30	0.06	0.18	16.75	0.07	0.19	⋯	5
SBS 1542+541	17.28	0.03	0.08	17.03	0.05	0.15	⋯	4
MK 876	14.85	0.05	0.12	14.49	0.03	0.07	⋯	5
TON 256	15.99	0.05	0.15	15.61	0.08	0.25	⋯	8
3C 332.0	15.88	0.11	0.36	15.38	0.05	0.15	⋯	8
MK 877	15.33	0.14	0.49	15.09	0.12	0.36	Smooth	9
KP 77	17.33	0.07	0.19	17.13	0.09	0.27	⋯	6

Name	Avg *V*	Std Dev	Min–Max	Avg *R*	Std Dev	Min–Max	Variability	Nights
HS 1626+6433	16.66	0.06	0.25	16.34	0.07	0.32	⋯	13
KUV 16313+3931	16.69	0.12	0.47	16.39	0.07	0.30	⋯	11
RX J17025+3247	16.20	0.24	0.82	15.90	0.15	0.50	⋯	12
3C 351.0	15.67	0.11	0.34	15.23	0.05	0.14	⋯	7
RX J17159+3112	15.81	0.06	0.19	15.46	0.04	0.14	⋯	15
PG 1718+481	15.10	0.05	0.22	14.66	0.02	0.08	⋯	14
4C 34.47	16.32	0.10	0.31	15.91	0.08	0.25	Smooth	10
H 1722+119	15.52	0.22	0.70	14.95	0.17	0.63	⋯	15
1ZW 187	15.90	0.06	0.23	15.37	0.04	0.15	Stochastic	15
IRAS 17500+5046	15.24	0.02	0.08	14.83	0.02	0.07	⋯	14
KAZ 102	16.57	0.07	0.20	16.24	0.05	0.15	⋯	12
KUV 18217+6419	14.23	0.02	0.08	13.87	0.02	0.07	⋯	13
PGC 61965	15.09	0.04	0.13	14.69	0.05	0.20	⋯	13
IRAS 18299+4113	16.22	0.03	0.08	15.73	0.13	0.56	⋯	14
HS 1946+7658	16.42	0.08	0.37	16.05	0.04	0.17	⋯	15
1ES 1959+650	14.95	0.13	0.46	14.39	0.11	0.39	Smooth	19
4C 74.26	14.69	0.02	0.06	14.14	0.02	0.07	⋯	20
MK 509	13.79	0.04	0.15	13.25	0.03	0.08	⋯	13
PG 2112+059	15.62	0.04	0.11	15.31	0.03	0.10	⋯	8
2ZW 136	14.77	0.06	0.18	14.41	0.03	0.12	⋯	12
OX+169	16.18	0.04	0.17	15.82	0.04	0.12	⋯	21

Name	Avg *V*	Std Dev	Min–Max	Avg *R*	Std Dev	Min–Max	Variability	Nights
IRAS 21431-0432	16.54	0.08	0.29	16.05	0.06	0.19	···	16
BL Lac	14.12	0.25	1.16	13.39	0.24	1.10	Stochastic	22
4c 31.63	15.61	0.04	0.13	15.21	0.04	0.18	···	21
ZW II 171 s	15.84	0.08	0.30	15.26	0.05	0.20	···	21
KUV 22497+1439	16.11	0.07	0.21	15.75	0.06	0.25	···	20
4C 11.72	15.86	0.05	0.27	15.41	0.04	0.14	···	19
MK 926	14.66	0.04	0.13	14.07	0.03	0.08	···	10
PB 5235	15.95	0.04	0.13	15.69	0.04	0.16	···	13
PB 5250	15.40	0.15	0.60	14.71	0.12	0.51	Smooth	14
4C 09.72	16.15	0.07	0.26	16.00	0.07	0.24	···	13
3C 465.0	13.67	0.05	0.22	12.96	0.03	0.12	···	15
4C 09.74	16.28	0.11	0.47	16.07	0.05	0.20	···	19
1ES 2344+514	15.38	0.05	0.21	14.62	0.04	0.14	···	18
PKS 2349-014	16.37	0.05	0.16	15.80	0.11	0.48	···	14

Thirteen blazars were confirmed as variable. Four were stochastic and nine were smooth. The four stochastic ones and their *R*-squared values for *V* and *R* are MK 1148 (0.33, 0.43), AO 0235+164 (0.24, 0.45), IZw 187 (0.41, 0.35), and BL Lac (0.21, 0.22). The nine smooth ones and their *R*-squared values are 3C 84 (0.82, 0.78), Mrk 421 (0.97, 0.96), RX J12302+2517 (0.97, 0.96), OQ+530 (0.86, 0.85), PKS 1424+240 (0.96, 0.97), 4C 34.47 (0.91, 0.85), MK 877 (0.70, 0.77), IES 1959+650 (0.89, 0.91), and PB 5250 (0.80, 0.74). Object AO 0235+164 had a particularly noteworthy flare, brightening by about 1.5 mag between the 2016 January 2nd and 12th.

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