OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** long-term* **Proposal ID:** L198

The γ-Ray/Optical Connection in Blazars During the Fermi Era

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Abstract of Scientific Justification

A 3-year proposal to continue funding a large-scale project providing optical linear spectropolarimetry and spectrophotometry of blazars monitored by the *Fermi Gamma-ray Space Telescope* until the end of 2018 has been submitted to NASA. If accepted, this telescope time request will begin the first year of this observing commitment. *Fermi* is now executing its primary science mission of observing the entire γ-ray sky every 3 hr after being successfully launched on June 11, 2008 and has a expected 10-year mission lifetime (funding limited). Given its vastly improved sensitivity over previous high-energy observatories, *Fermi* is able to monitor the 20 MeV – 300 GeV emission from the brightest 2 dozen or so γ-ray–detected blazars on a daily basis. The optical project supports the *Fermi* mission with daily monitoring of blazars using the Bok and Kuiper telescopes and the SPOL spectropolarimeter. These data are combined with measurements by *Fermi* and associated radio campaigns to investigate connections between the γ-ray, optical, and radio emission in blazars and to constrain models of the relativistic jets producing the observed variable, polarized continuum. The Steward Observatory polarimetry provides unique information on the magnetic field within the continuum emission regions of blazars and has shown that there is often a strong connection between the optical and γ-ray emission. Observations will be obtained during $\sim$1 week per month and completes the proposal submitted for 2015A that was granted long-term status.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	90” or 61”	f/9-13	SPOL	*		7	dark	Sep	Sep–Oct	yes	no
2	90” or 61”	f/9-13	SPOL	*		7	dark	Oct	Sep–Oct	yes	no
3	90” or 61”	f/9-13	SPOL	*		7	dark	Nov	Nov–Dec	yes	no
4	90” or 61”	f/9-13	SPOL	*		7	dark	Dec	Nov–Dec	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: **Either 90″ or 61″ telescopes can be used for any given observing run**, but the 90″ is preferred if scheduling pressures allow. Allocated time *needs* to be scheduled in at least 1-week-long blocks. Other programs utilizing SPOL at the 90″ or 61″ telescopes are possible this semester, but it is desirable that SPOL be scheduled in contiguous blocks of time to minimize instrument changes.

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A * appended to the proposal type indicates a continuation proposal; a * appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a $*$ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	MG1 J021114+1051	02:11:13.18	+10:51:34.8	V=16.5
2	3C 66A	02:22:39.60	+43:02:08.0	V=15.5, z=0.444, TeV source
3	4C 28.07	02:37:52.41	+28:48:09.0	V=18.5, z=1.207
4	PKS 0235+164	02:38:38.93	+16:36:59.3	V=19.0, z=0.940
5	VER J0521+211	05:21:45.00	+21:12:51.4	V=18.5, z=0.108, TeV source
6	PKS 0454−234	04:57:03.18	−23:24:52.0	V=18.5, z=1.003
7	S5 0716+71	07:21:53.45	+71:20:36.4	V=14.2, z=0.300, TeV source
8	BZU J0742+5444	07:42:39.80	+54:44:24.7	V=16.9, z=0.723
9	OJ 248	08:30:52.09	+24:10:59.8	V=17.4, z=0.940
10	OJ 287	08:54:48.87	+20:06:30.6	V=14.0, z=0.306
11	S4 1030+61	10:33:51.42	+60:51:07.4	V=19.0, z=1.401
12	Mrk 421	11:04:27.31	+38:12:31.8	V=13.3, z=0.030, TeV source
13	W Com	12:21:31.69	+28:13:58.5	V=16.5, z=0.102, TeV source
14	PKS 1222+216	12:24:54.46	+21:22:26.4	V=17.5, z=0.435, TeV source
15	3C 273	12:29:06.70	+02:03:08.6	V=12.9, z=0.158
16	3C 279	12:56:11.17	−05:47:21.5	V=17.8, z=0.536, TeV source
17	H 1426+428	14:28:32.66	+42:40:20.6	V=16.8, z=0.129, TeV source
18	PKS 1502+106	15:04:24.98	+10:29:39.2	V=15.5, z=1.839
19	PKS 1510−08	15:12:50.53	−09:05:59.8	V=16.5, z=0.360, TeV source
20	Mrk 501	16:53:52.22	+39:45:36.6	V=14.2, z=0.034, TeV source
21	1ES 1959+650	19:59:59.85	+65:08:54.7	V=12.8, z=0.048, TeV source
22	PKS 2155−304	21:58:52.07	−30:13:32.1	V=14.0, z=0.116, TeV source
23	BL Lac	22:02:43.29	+42:16:40.0	V=14.5, z=0.069, TeV source
24	3C 454.3	22:53:57.75	+16:08:53.6	V=16.1, z=0.859
25	PMN J2345-1555	23:45:12.46	−15:55:07.8	V=18.0, z=0.621
26	1ES 2344+514	23:47:04.84	+51:42:17.9	V=12.9, z=0.044, TeV source

Approval for Instrument Use from PI: _____

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Progress Report for "The Gamma-ray/Optical Connection in Blazars During the Fermi Era"

Optical spectropolarimetric and spectrophotometric monitoring of γ-ray-bright blazars using the facilities of Steward Observatory (SO) in support of the *Fermi Gamma-ray Space Telescope* began in 2008 October. Since then, 70 monthly observing campaigns, each spanning at least a week, have been completed by the SO 2015B proposal submission deadline. Over 8000 spectropolarimetric observations of $\sim$60 blazars have been made as of the beginning of 2015 March. Nearly 6500 flux measurements have also been obtained for this sizable sample of γ-ray sources. These data provide a unique and comprehensive *public* record of the optical linear polarization, flux, and spectral variability of γ-ray–bright active galactic nuclei (AGNs) during the *Fermi* mission.

Since the launch of *Fermi* until the end of 2015 July (the end of Cycle 7 of the mission), the SO Telescope Allocation Committee (TAC) has awarded the optical monitoring project a total of 530 nights, with 287 nights (54%) scheduled at the 2.3 m Bok Telescope and 243 nights scheduled at the 1.54 m Kuiper Telescope. Most observing campaigns have been extremely fortunate with the weather and have been highly productive. In fact, time lost to weather has largely been offset by utilizing 22 unscheduled nights on these telescopes and occasional observations obtained during the course of other science programs employing the same spectopolarimeter. In total, at least some polarization data have so far been obtained on 518 nights for blazars monitored at high energies by the Large Area Telescope (LAT) aboard *Fermi*.

This telescope time request is for continued monthly campaigns from 2015 September – December to complete the long-term SO program L198 and to begin supporting observations for *Fermi* Cycle 8. As usual, these nights will be split into monthly, 7-night observing campaigns. In practice, each campaign will be lengthened to 9–10 contiguous nights because of unrelated science programs (if granted time by the TAC) utilizing the SPOL spectropolarimeter that are "piggybacked" onto the *Fermi* time allocation. Since the beginning of 2012, observations for various programs have been intermixed during the augmented campaigns. This strategy has been beneficial to the blazar monitoring program by both extending the period in which the polarization and flux of targets can be monitored on daily time scales and by better insulating all SPOL programs from bad weather.

As designed, the monitoring program is delivering nightly high signal-to-noise ratio (S/N) linear polarization, flux, and spectral information for 50–60 blazars that *Fermi* has been able to detect on time scales of a few days or less (Abdo et al. 2009; 2010). For blazars in the brightness range of $V \sim 13$–17, typical of the *Fermi*-selected sample being monitored, very high-S/N polarimetry ($\sigma_P \lesssim 0.1$%) is being routinely achieved. For the faintest targets in the LAT-monitored source list, $\sigma_P \lesssim 1.0$% has been achieved for $V \sim 20.3$. This high degree of accuracy means that small variations in linear polarization can be tracked even when a blazar is faint and/or not highly polarized. Additionally, the highly accurate polarimetry is well suited for comparison to contemporaneous high-resolution radio maps of the polarized flux being obtained by facilities such as the Very Long Baseline Array in support of *Fermi*. It has been found over the past decade and early in the *Fermi* mission that rapid, systematic rotations in the optical polarization position angle (θ) are often associated with major flaring events spanning γ-ray through radio wavelengths (see e.g., Agudo et al. 2011b). In particular, these rotations in θ have been important features in proposed models of γ-ray flares in BL Lacertae (Marscher et al. 2008), PKS 1510$-$089 (Marscher et al. 2010), and 3C 279 (Abdo et al. 2010). The comprehensive modeling of the flaring behavior of PKS 1510$-$089 is one of the early results from the *Fermi* multi-wavelength program and the monitoring done at SO provided a major source of polarization data, as it has for the detailed analyzes of the behavior of 3C 454.3 (Jorstad et al. 2010; 2013), OJ 287 (Agudo et al. 2011a), AO 0235+16 Agudo et al. 2011b), 4C 38.41 (Raiteri et al. 2012), and BL Lacertae (Raiteri et al. 2013).

Evidence that the γ-ray and optical emission may originate from the same region within the relativistic jet is shown in **Figure 1**. Here, the LAT 0.1–300 GeV measurements of 3C 454.3 are shown along with the optical observations made on 337 nights using the SO 2.3 m Bok and 1.54 m Kuiper telescopes with the SPOL spectropolarimeter during the first 6 years of the *Fermi* mission. The top panel of the figure shows the

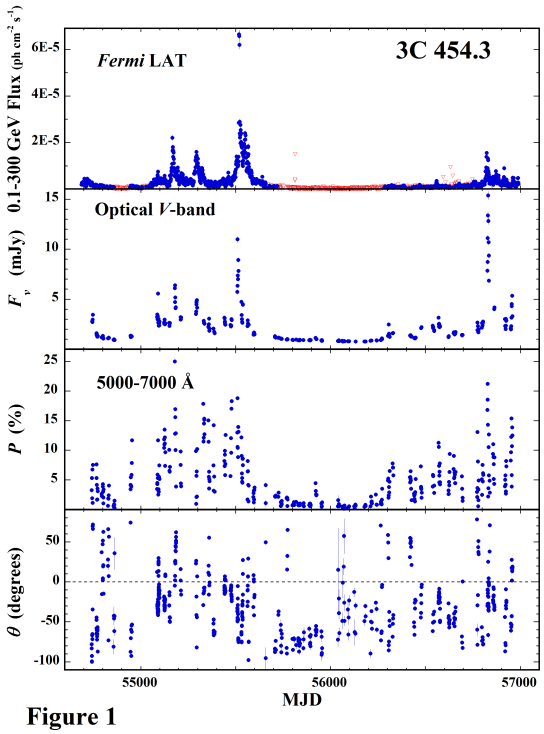

Figure 1

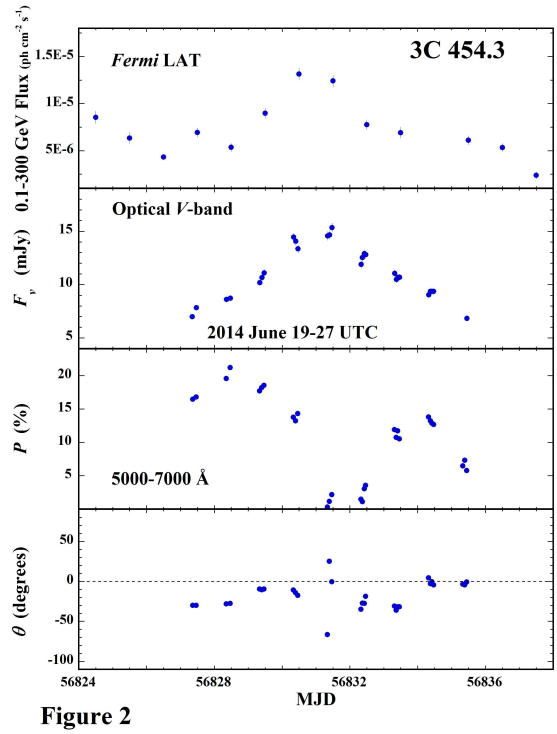

Figure 2

impressive variability in γ-ray flux as measured by the LAT, with daily upper limits denoted by red triangles. It is clear that the optical flux activity (second panel) closely follows the changes seen at GeV energies. The variability of the degree of linear polarization (P; third panel) is also more pronounced during periods of high flux and $P > 10\%$ is only observed during active periods. Like P, the polarization position angle (θ; bottom panel) is generally more stable during periods when the γ-ray and optical fluxes are low.

Monitoring blazars over long periods of time in conjunction with *Fermi* has led to the important discoveries of trends between the optical and γ-ray emission in blazars. In one of the most detailed multi-wavelength investigations of a blazar so far, recurring behavior in the γ-ray through radio variability was identified in 3C 454.3 during three high-energy outbursts spanning 2009–10 (Jorstad et al. 2013). This suggests that a similar mechanism at possibly the same location within the jet gives rise to the flares. After this period, 3C 454.3 became quiescent for over two years. In 2014 June, the object underwent its first major outburst since the unprecedented flare in late 2010 and the SO monitoring data show the optical flux and polarization behavior to be similar to the earlier large flares. **Figure 2** displays the γ-ray and optical data from 2014 June. A remarkable drop in polarization from over 20% to essentially 0% is seen in only three days. Like the earlier flares, the polarization peaks before the optical flux peak and drops as both the optical and γ-ray fluxes reach their maxima. A possibility for explaining this behavior is that the emitting plasma enters a turbulent, shocked region where the magnetic field becomes so chaotic that the polarization falls to low values, while the shock front boosts the observed flux. An alternative explanation could have a high degree of symmetry in the magnetic field within the emitting region that can produce levels of polarization higher than 20%. If the axis of symmetry of the magnetic field is along the jet axis, then the beamed radiation will naturally increase while the polarization drops when the jet becomes better aligned with our line of sight.

Binned high-S/N polarimetry, full-resolution linear Stokes spectra, synthetic broad-band differential photometry, and full-resolution flux spectra are all available to researchers from the SO program website at:

$$\texttt{http://james.as.arizona.edu/}^{\sim}\texttt{psmith/Fermi}\,.$$

The website has been designed to also provide detailed information as to how observations are made and the data reduced, so that investigators incorporating the results from the SO program into their analysis of blazar variability are familiar with the quality and limitations of the data products presented. Generally, the data

acquired during an observing campaign are fully reduced and available at the website by the start of the next campaign in the following month, although there are instances when more time is needed if an exceptionally large amount of data is acquired. At the submission deadline for this Progress Report, data reduction and processing are complete through the end of 2015 February and all of the measurements are available to the research community.

References

Abdo, A.A., et al. 2009, ApJ , 700, 597
Abdo, A.A., et al. 2010, ApJ , 715, 429
Agudo, I., et al. 2011a, ApJ , 726, L13
Agudo, I., et al. 2011b, ApJ , 735, L10
Jorstad, S.G. et al. 2010, ApJ , 715, 362
Jorstad, S.G. et al. 2013, ApJ , 773, 147
Marscher, A.P., et al. 2008, Nature , 452, 966
Marscher, A.P., et al. 2010, ApJ , 710, L126
Raiteri, C.M., et al. 2012, A&A , 545, 48
Raiteri, C.M., et al. 2013, MNRAS , 436, 1530
Smith, P.S. 2010, ATEL#2831
Smith, P.S., & Bechetti, G.J. 2010, ATEL#2623

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Very successful observing strategies have been developed in the early years of the *Fermi* mission for using SPOL at both the Bok and Kuiper telescopes to maximize the information obtained with each observation. SPOL is a highly efficient dual-beam polarimeter, designed and built by one of the co-investigators (Schmidt), with a measured total throughput (telescope + instrument) of $\sim$30%. Its dual-beam design enables simultaneous measurement of both senses of polarization and the associated background. As a result, polarization measurements are insensitive to atmospheric transparency and seeing variations during an observation. Not having a requirement that the sky be strictly photometric to obtain accurate polarimetry has greatly increased the yield of data during the monitoring program. The SO program routinely produces some of the highest quality polarization and spectral information available for blazars and provides uniform data products to the research community. These data are suitable for both purely optical studies of sample objects and, as intended, for combination with data obtained at other wavelengths

Typically, SPOL is configured in its spectropolarimetric mode so that flux-calibrated spectra of targets can be obtained. Our work during the past six years reveals that adequate polarimetry and photometry of targets as faint as $V \sim 19$ can be obtained in this observing mode within 1–2 hr in dark skies with the Bok Telescope. The instrument can be reconfigured within minutes for imaging polarimetry if broad-band polarimetry is desired for even fainter targets. Both Bok and Kuiper telescopes have demonstrated the capability to provide very high-S/N measurements.

The structure of the observing program will remain unchanged at roughly one week-long campaign each month. This observing cadence enables a period of intensive, nightly monitoring of the sample each month that can be compared to the daily γ-ray measurements from the LAT. Continued monitoring over monthly time scales allows for the optical data to be compared with the results of the long-term VLBI monitoring programs associated with the *Fermi* mission.

The SO program is kept flexible to rapidly respond to high-energy events announced by the *Fermi* Collaboration and from the ground-based Cherenkov telescopes. For example, responding to announcements of new γ-ray activity detected by the LAT from ambiguous sources, we were able to identify the likely optical counterparts within 24 hr (Smith & Bechetti 2010; Smith 2010). In both cases, the initial observations with SPOL identified the counterparts as blazars undergoing optical outbursts and showing high polarization.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

The SO monitoring program has made impressive progress using SPOL at the Bok and Kuiper telescopes since the launch of *Fermi* and has played its intended role in the large multi-wavelength variability studies cited in the Progress Report. The SO TAC has allocated well over a full year of telescope time from the beginning of the *Fermi* mission through to the end of Cycle 7 (2008 October–2015 July) for supporting optical observations. The monitoring program is now undergoing a NASA review in 2015 spring under the *Fermi* Cycle 8 Guest Investigator Program that will determine if the agency will fund optical observations at SO until the planned end of the γ-ray observatory's mission in 2018.

The favorable institutional support for the program over the past seven years can be gauged by the fact that 54% of the nights assigned have been for the larger Bok Telescope and that almost all of the time granted has been for periods when the moon does not hamper observations. Data have been collected on 518 nights through 2014 February 20, with some of the inevitable losses due to weather made up by utilizing 22 open nights at the telescopes. This huge investment in resources has resulted in a fully public archive of over 8000 linear polarization and flux spectra, along with $\sim$6500 differential photometric measurements of $\sim$60 γ-ray–bright blazars by 2015 March. By delivering over 1000 observations per year, the SO program is achieving its stated goal of providing to the research community a comprehensive data set for a large number of the γ-ray–bright blazars that augments both the LAT and VLBI monitoring.

Generally, dark sky conditions are requested for each observing campaign. Not having a bright moon in the sky greatly improves the effectiveness of the program, as more targets can be observed per night without the presence of a bright, highly polarized background. Importantly, fainter sources ($V \sim 18$–20) can still be successfully observed, at least with the Bok Telescope. Because of the capability to reach faint flux levels, the program is not overly biased by observing sources only when they are optically bright.

The factor of 2 increase in sensitivity offered by the Bok Telescope and its ability to point at targets north of +61° make it the preferred choice for the monitoring program. However, we realize that this project demands a large fraction of available dark time on general-use telescopes to provide the maximum level of support for the *Fermi* mission given manpower constraints. Therefore, the Kuiper Telescope is an acceptable alternative when scheduling pressures from equivalently (or higher) ranked science programs that require the 90-inch telescope are encountered. By using both telescopes, we have been able to avoid undesired gaps in the optical monitoring and create a truly unique and comprehensive optical record of the behavior of γ-ray–bright blazars during the *Fermi* era.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

Smith and Jannuzi continued to make extensive and effective use of SO facilities, especially the Bok and Kuiper Telescopes, over the past two years. During this period, the Steward/*Fermi* blazar monitoring program has dominated our use of Steward Observatory facilities. In addition, over the past decade, we have made a concerted effort to use both the SO 90″ and 61″ telescopes, in conjunction with VLBI monitoring of blazars, to directly connect the optical polarized flux with resolved structures within the radio jets. This work has resulted in several papers, including a letter to *Nature* (Marscher et al. 2008, Nature, 452, 966), that have been able to infer that the location of much of the unresolved optical emission is from the jet by documenting events where the optical polarization variations are tracked closely by the high-frequency radio core polarization.

Papers appearing in **refereed** journals within the last 2–3 years that make use of data acquired at SO telescopes are listed below.

"A Spectacular Outflow in an Obscured Quasar", Greene, J.E., Zakamska, N.L, & Smith, P.S. 2012, ApJ , 746, 86

⋆ "Search for Correlations Between the Optical and Radio Polarization of Active Galactic Nuclei - II. VLBA Polarization Data at 12+15+22+24+43 GHz", Algaba, J.C., Gabuzda, D.C., & Smith, P.S. 2012, MNRAS , 420, 542

⋆ "Variability of the Blazar 4C 38.41 (B3 1633+382) from GHz frequencies to GeV Energies", Raiteri, C.M., Villata, M., Smith, P.S., et al. (Carleton) 2012, A&A , 545, 48

⋆ "Multi-Wavelength Observations of Blazar AO 0235+164 in the 2008-2009 Flaring State", Ackermann, M., et al. 2012, ApJ , 751, 159

⋆ "Rapid TeV Gamma-Ray Flaring of BL Lacertae", Arlen, T., et al. (Smith) 2013, ApJ , 762, 92

⋆ "Flare-Like Variability of the Mg II λ2800 Emission Line in the γ-Ray Blazar 3C 454.3", Len-Tavares, J., et al. 2013, 763, L36

"Time-Resolved Spectroscopy of the Polar EU Cancri in the Open Cluster Messier 67", Williams, K.A., Howell, S.B., Liebert, J., Smith, P.S., Bellini, A, Rubin, K.H.R., & Bolte, M. 2013, AJ , 145, 129

⋆ "A Tight Connection between Gamma-Ray Outbursts and Parsec-scale Jet Activity in the Quasar 3C 454.3", Jorstad, S.G., Marscher, A.P., Smith, P.S., et al. 2013, ApJ , 773, 147

"Candidate Type II Quasars at $2 < z < 4.3$ in the Sloan Digital Sky Survey III", Alexandroff, R., Strauss, M.A., Greene, J.E., Zakamska, N.L., Ross, N.P., Brandt, W.N., Liu, G., Smith, P.S., Ge, J., Hamann, F., Myers, A.D., Petitjean, P., Schneider, D.P., Yesuf, H., & York, D.G. 2013, MNRAS , 435, 3306

⋆ "The Awakening of BL Lacertae: Observations by Fermi, Swift and the GASP-WEBT", Raiteri, C.M., et al. (Smith) 2013, MNRAS , 436, 1530

⋆ "Discovery of a New TeV Gamma-Ray Source: VER J0521+211", Archambault, S., et al. (Smith) 2013, ApJ , 776, 69

⋆ "A Time-resolved Study of the Broad-line Region in Blazar 3C 454.3", Isler, J.C., Urry, C.M., Coppi, P., Bailyn, C., Chatterjee, R., Fossati, G., Bonning, E.W., Maraschi, L., & Buxton, M. 2013, ApJ , 779, 100

⋆ "Comprehensive Monitoring of Gamma-Ray Bright Blazars. I. Statistical Study of Optical, X-Ray, and Gamma-Ray Spectral Slopes", Williamson, K.E., et al. (Smith; Schmidt) 2014, ApJ , 789, 135

"Multi-Epoch Spectropolarimetry of SN 2009ip: Direct Evidence for Aspherical Circumstellar Material", Mauerhan, J., Williams, G.G., Smith, N., Smith, P.S., Filippenko, A.V., Hoffman, J.L., Milne, P., Leonard, D.C., Clubb, K.I., Fox, O.D., & Kelly, P.L. 2014, MNRAS , 442, 1166