IMAGING REDSHIFT ESTIMATES FOR FERMI BL LAC OBJECTS

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ABSTRACT

We have obtained WIYN and SOAR \(i'\) images of BL Lacertae objects and used these to detect or constrain the flux of the host galaxy. Under common standard candle assumptions, these data provide estimates of, or lower bounds on, the redshift. Our targets are a set of flat-spectrum radio counterparts of high flux Fermi Large Area Telescope sources, with sensitive spectral observations showing them to be continuum-dominated BL Lac objects. In this sample, 5 of 11 BL Lac objects yielded significant host detections, with standard candle redshifts \(z = 0.13–0.58\). Our estimates and lower bounds are generally in agreement with other redshifts estimates, although our \(z = 0.374\) estimate for J0543–5532 implies a significantly sub-luminous host.

Key words: BL Lacertae objects; general – galaxies; jets

Online-only material: color figures

1. INTRODUCTION

BL Lac objects are an important, extreme sub-class of active galactic nuclei (AGNs). The large numbers of BL Lac objects being detected in the gamma-rays by the Fermi Large Area Telescope (LAT; Ackermann et al. 2011) show that these blazars are a dominant contributor to the GeV sky. This flux-limited gamma-ray sample also provides a unique opportunity to probe the evolution of the BL Lac object phenomenon over cosmic time (Ajello et al. 2014). BL Lac object evolution is controversial, with various authors finding negative (e.g., Rector et al. 2000), positive (e.g., Marcha & Caccianiga 2013), or negligible evolution (e.g., Caccianiga et al. 2002). Much of this uncertainty stems from the difficulty in determining redshifts; for many BL Lac objects, the high jet-associated continuum flux dominates emission from any broad-line region and results in very low equivalent width for galactic host absorption features. Despite intensive spectroscopic campaigns (Shaw et al. 2013a), this often precludes direct BL Lac object redshift measurements, challenging their utility for population and evolution studies (Ajello et al. 2014). Thus alternate methods of estimating or constraining the source redshift can be quite valuable (Shaw et al. 2013b).

In this paper, we image Fermi BL Lac objects to search for host flux in the wings of the nuclear point-spread function (PSF). Our targets are drawn from the “2LAC” (Ackermann et al. 2011) LAT blazars for which sensitive spectroscopy, reported in Shaw et al. (2013a), shows them to be continuum-dominated BL Lac objects at very high significance but was not able to determine a redshift. Since hosts are increasingly difficult to detect at high redshift, we excluded BL Lac objects whose spectra showed intervening absorbers requiring \(z > 0.7\) or excluded continuum flux from hosts at lower \(z\). This left 226 targets. We observed objects from this list when conditions and gaps in other observing programs allowed.

It has been argued that BL Lac object hosts are nearly uniform giant ellipticals with \(M_B = -22.5\) (Sbarufatti et al. 2005). Thus several authors have used such imaging to constrain the source redshift (e.g., Sbarufatti et al. 2005; Meisner & Romani 2010; Nilsson et al. 2012). One can also search for the elliptical flux in high signal-to-noise (S/N) spectra; when not detected, this provides a lower limit on the redshift (e.g., Sbarufatti et al. 2006; Shaw et al. 2013a; Sandrinelli et al. 2013). Conversely, when direct spectroscopic redshift measurements are in hand (or later become available), the flux measurements can be used to test the standard candle hypothesis and the evolution of the BL Lac object hosts. Here, we follow the method described by Meisner & Romani (2010), although we use an updated host magnitude calibration derived from absorption features measured in a deep spectroscopic survey (Shaw et al. 2013b).

2. OBSERVATION AND DATA REDUCTION

Our typical BL Lac object has a total magnitude of \(i' \sim 15–18\). We wish to model our individual image PSF, following the wings to well below the sky brightness, and to test the PSF model against a number of stars with flux comparable to that of the BL Lac object core. Thus we need moderate field imaging with good natural seeing. For this program, we used the Mini-Mosaic (MiniMo) camera at the WIYN 3.6 m telescope at Kitt Peak National Observatory and the SOAR Optical Imager (SOI) at the SOAR 4.2 m telescope on Cerro Pachon. Individual exposures \((t_{\text{exp}} = 180 \text{ s}–600 \text{ s})\) were adjusted to minimize the core saturation; the pointing was dithered between exposures. All data were taken using a Sloan Digital Sky Survey (SDSS) \(i'\) filter.

2.1. MiniMo

Observations with MiniMo were made on the nights of 2011 September 26–27 and 2012 February 17–18. The mosaic image consists of two \(2048 \times 4096\) chips, with a plate scale of \(0'.141/\text{pixel},\) separated by a \(7''.8\) gap. This gives a field of \(9.6 \text{ arcmin} \times 9.6 \text{ arcmin}\).

2.2. SOI

Observations with SOI were made on the nights of 2012 March 21–23. The SOI mosaic also has two \(2048 \times 4096\) chips,
again split by a 7′′/12 gap. Seeing was only moderate quality during the run, so we observed with 2 × 2 binning, for a plate scale of 0′.153/binned pixel and a 5.2 arcmin × 5.2 arcmin field of view. We targeted five dithered exposures for each object. We generally suffered significant core saturation for the brighter BL Lac objects.

2.3. Data Processing

All images were reduced using the IRAF mscred package for mosaic image data. Standard zero image bias subtraction and dome flats were applied and cosmic rays were cleaned using the IRAF xzap package. A few bad pixel/cosmic ray events were edited by hand. The i′ fringing was quite modest, especially for the chip hosting the BL Lac object target, so no fringe corrections were made.

After generation of a world coordinate system for each frame using the USNO B-1 reference catalog, the dithered frames were stacked to a median combined frame. In general, the PSF varied relatively slowly during the observations. In a few cases, we rejected the worst sub-frames before the final image combination. The final exposures included in the image stack and the stacked image FWHM are listed in Table 1.

### 3. Image Modeling

Our goal is to measure the unresolved AGN core and surrounding resolved host galaxy, extracting reliable fluxes or flux upper limits for the latter. To this end, we model cut-outs around each BL Lac object. Typically we treated a 10″ × 10″ region, although for one object we used a 22″ × 22″ region to contain the bulk of the host counts, and for two other objects we were able to reduce the region size to 6″ × 6″ while containing all the host flux.

#### 3.1. Model Components

Since we are interested in the faint host excess in the wings of the AGN PSF, we need an accurate PSF for each final combined image frame. These PSFs were generated using the IRAF daophot package. Generally, more than 20 bright isolated stars were available to generate the PSF, although a few fields were more sparse. Saturated stars were not included in the PSF stack. For most cases, our PSF model extends to 5″, where the host contribution drops well below the sky, however for two objects with the best PSF we used 3″ and for the target with the worst seeing we extended the PSF model to 11″. Since we needed much of the field to include sufficient bright stars, we used a quadratic variation across the image for the analytic PSF core. The accuracy of the PSF model was checked by generating a model (using the quadratic position-dependent PSF) for the precise positions of a set of check stars in each image. The residuals after subtraction were very small well out into the PSF wings, although as expected, poor subtraction was often present for near-saturated cores within 1 FWHM. The target PSF model was generated for the field position of the BL Lac object.

Based on previous studies of BL Lac object host galaxies (Scarpa et al. 2000; Urry et al. 2000), we assume that our hosts are well modeled by a de Vaucouleurs profile of Sersic index 4. In addition to the integrated model flux, we have up to three shape parameters. For bright, well-resolved hosts, we can fit the effective angular size θe. For other sources we fix this at θe = 1′.65, which corresponds to Re = 10 kpc at a typical BL Lac object z = 0.5 for our standard approximate concordance cosmology (Ωm = 0.3, ΩΛ = 0.7, H0 = 70 km s−1 Mpc−1). Occasionally resolved hosts show significant ellipticity; we then fit this along with the position angle. Before fitting, the model profile is convolved with the locally generated model PSF for the particular image.

#### 3.2. Fitting Procedure

In all cases, we use the AGN core position (fit with IRAF DAOPHOT) determined at sub-pixel accuracy to generate the normalized templates for the PSF and PSF-convolved host models. The core and host position were not adjusted in the fit. Before fitting, we masked saturated pixels (counts > 35,000DN), which typically excluded ∼1 FWHM around the PSF core and for the brightest sources, a modest number of pixels in a bleed trail. We also had the option of masking pixels associated with neighboring sources (companion galaxies and field stars). This was done for three sources.

We fit the masked cut-out images with χ2 minimization of the residuals to the model counts in each image pixel, using a Nelder–Mead downhill simplex algorithm.2 Host shape parameters are determined hierarchically. If a statistically significant amplitude is fit (>3σstat) using the default spherical host with

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**Table 1**

| Name          | SIMBAD Name | Tel | Exp (s) | DIQ (″) | NPSF | Corea | Hosta | σstat a | σsys a |
|---------------|-------------|-----|---------|---------|------|-------|-------|---------|--------|
| J0114+1325    | GB6 J0114+1325 | W   | 3 × 300 | 0.72    | 26   | 2160  | 144   | 5.47    | 43.8   |
| J0115+2519    | RX J0115.7+2519 | W   | 3 × 300 | 0.79    | 21   | 1050  | 377   | 5.27    | 18.8   |
| J0222+4302    | 3C 66A      | W   | 5 × 300 | 0.68    | 36   | 13500 | 229   | 7.77    | 315.   |
| J0316+0904    | GB6 J0316+0904 | W   | 5 × 300 | 0.63    | 27   | 1910  | 133   | 4.18    | 61.5   |
| J0543–5532    | 1RXS 053810.0–390839 | S   | 5 × 300 | 0.57    | 20   | 3410  | 638   | 6.82    | 108.   |
| J0558–7459    | PKS 0600–749 | S   | 5 × 180 | 0.69    | 24   | 1260  | −24   | 7.29    | 56.7   |
| J0700–6610    | PKS 0700–661 | S   | 4 × 300 | 1.06    | 19   | 4950  | 81    | 6.70    | 147.   |
| J0721+7120    | SS 0716+71  | W   | 600 + 3 × 300 | 1.34 | 19   | 39700 | 5430  | 16.0    | 812.   |
| J1023–4336    | RX J1023.9–4336 | S   | 5 × 300 | 0.62    | 21   | 8610  | 120   | 10.3    | 106.   |
| J1026–8543    | PKS 1029–85 | S   | 1 × 300 | 0.83    | 16   | 2150  | 10    | 6.21    | 88.6   |
| J1110–1835    | CRATES J1110–1835 | S   | 5 × 180 | 0.61    | 9    | 372   | 9     | 3.84    | 20.0   |

Notes. Tabulated quantities: name, SIMBAD name, telescope, exposure used, final combined image full width at half maximum, number of PSF stars used, fit core (PSF) count rate, fit host count rate, statistical error on host rate, estimated systematic error on host rate.

*counts s−1.

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[2] docs.scipy.org/scipy.optimize.fmin.html
fixed $\theta_e$, we refit allowing $\theta_e$ to vary. If $\theta_e$ is measured with high statistical significance, we refit including the ellipticity and position angle of the host. In this data set, only three sources had a well-measured effective radius and only one had significant ellipticity. The routine returns best fit values for the PSF, host, and constant background counts, up to three additional host shape parameters, and statistical errors on each fit quantity.

### 3.3. Systematic Errors

Inevitably, due to peculiarities of the actual image and imperfections in the model PSF, we expect systematic errors to dominate the simple fit statistical errors. To estimate the systematic errors on the host fitting, we selected $\sim10$ bright stars in each image, generated the local PSF and fit for combined PSF, de Vaucouleurs (fixed $\theta_e$) “host”, and uniform background counts. Ideally these would not be drawn from the PSF stars, but we did not always have enough bright stars to avoid overlap.

The fit “host” counts give an estimate of the systematic host errors. Figure 1 shows the distribution of fit “host” counts as a fraction of the stellar PSF counts. The mean of zero suggests good model PSFs with no overall bias.

In Figure 2, we show the absolute value of the individual fit “host” counts plotted as a function of PSF counts. If the errors were purely statistical, we would expect a square-root scaling. Instead, the upper envelope of the distribution is approximately linear (solid line), suggesting that the dominant errors are indeed linear (solid line), suggesting that the dominant errors are indeed systematic for bright PSFs. The final fit component counts and the statistical and systematic errors are listed in Table 1. We also list the calibrated core fluxes and host flux ratios in Table 2, where we convert $i'$ magnitudes to instrument band flux using calibration stars from the SDSS.

To claim a significant host detection, we require that the fit counts exceed $\sqrt{3}\sigma_{\text{stat}} + \sigma_{\text{sys}}$. Four of our BL Lac object hosts are detected at very high significance. Two are seen with somewhat lower confidence, with J0316+0904 having $\sim2.2\sigma_{\text{sys}}$ significance and J1023−4336 appearing at $\sim1.1\sigma_{\text{sys}}$ (although both are of high statistical significance). Visual inspection of the images and the azimuthally average radial profile plots (below) confirm that the former is a very likely detection. However, the latter, while a plausible detection, may be more safely treated as an upper limit. When we have no significant host detection, we infer host flux counts to be $<\sqrt{3}\sigma_{\text{stat}} + \sigma_{\text{sys}}$.

Only three sources have significant $R_e$ measurements listed. These well-measured sizes are all consistent with the standard 10 kpc assumption. J0115+2519 was the only source with a statistically significant ellipticity $e = 0.160 \pm 0.043$; this is at major axis position angle $-16:1 \pm 3:5$, measured north through east.

It is convenient to display these fits as azimuthally averaged profiles of the surface brightness. In Figure 3, we show two sources with well-detected hosts. Figure 4 shows two sources with radial profiles well matched to the PSF, resulting in host upper limits. Error flags on the data curves show the 1σ fluctuations assuming Poisson statistics.
To this end, we use the Hubble diagram curve to constrain the source redshift, adopting the standard candle in our standard cosmology, computing the observed flux by \( z \) the Fioc & Rocca-Volmerange (1997) models to the observed 

**Figure 3.** Two objects with significant host detections. Left: J0114+1325 (WIYN). Right: J0543-5532 (SOAR). The inferred redshifts are \( z \approx 0.58 \) and \( z \approx 0.37 \), respectively. The lines show the profile of the best-fit model components, converted to mag arcsec\(^{-2}\). For both, the host counts dominate the PSF beyond \( \sim 2'' \).

(A color version of this figure is available in the online journal.)

| Name          | SED\(^a\) | \( i'_{\text{nucl}} \) | \( i'_{\text{host}} \) | \( f_{\text{host}}/f_{\text{nucl}} \) | \( R_e \) (kpc) | \( z_{\text{im}} \) | \( z_{\text{up}} \) |
|---------------|-----------|----------------|----------------|----------------|---------------|-------------|-------------|
| J0114+1325    | H         | 17.21          | 20.15\( ^{+0.038}_{-0.037} \) | 0.07          | 8.32 \( ^{+0.14}_{-0.06} \) | 0.583 \( ^{+0.073}_{-0.056} \) | 0.61–1.63  |
| J0115+2519    | H         | 17.68          | 18.80\( ^{+0.015}_{-0.015} \) | 0.36          | 12.53 \( ^{+0.55}_{-0.01} \) | 0.358 \( ^{+0.014}_{-0.001} \) | 0.37–1.63(0.268) |
| J0222+4302    | I         | 15.13          | >19.21          | <0.02         | ...            | >0.42       | 0.12–1.67  |
| J0316+0904    | H         | 16.01          | 18.91\( ^{+0.016}_{-0.033} \) | 0.07          | ...            | 0.374 \( ^{+0.065}_{-0.004} \) | 0.12–1.66  |
| J0543–5532    | H         | 17.10          | 18.92\( ^{+0.012}_{-0.012} \) | 0.19          | ...            | 0.374 \( ^{+0.032}_{-0.002} \) | 0.27–2.57(0.273) |
| J0558–7459    | ...       | 17.23          | >20.52          | <0.05         | ...            | >0.66       | 0.29–2.20(0.475) |
| J0700–6610    | I         | 16.28          | >20.08          | <0.03         | ...            | >0.57       | 0.39–1.92  |
| J0721+7120    | I         | 14.01          | 16.17\( ^{+0.038}_{-0.002} \) | 0.14          | 9.54 \( ^{+0.32}_{-0.02} \) | 0.127 \( ^{+0.02}_{-0.001} \) | 0.14–2.61  |
| J1023–4336    | H         | 15.26          | 19.90\( ^{+0.090}_{-0.096} \) | 0.03          | b \( 0.53_{-0.14}^{+0.003} \) | 0.43–2.24  |
| J1026–8543    | L         | 16.88          | >20.31          | <0.04         | ...            | >0.62       | 0.32–2.30  |
| J1110–1835    | L         | 18.69          | >21.70          | <0.06         | ...            | >0.93       | 0.51–2.23  |

Notes. Tabulated quantities: name, SED class, core magnitude, host magnitude and errors or limit, host/core flux ratio host radius, inferred redshift or limit, spectroscopic constraints on redshift.

\(^a\) SED class from Ackermann et al. (2011), based on the synchrotron peak frequency.

\(^b\) Good statistical, but marginal \( \sim 1\sigma \) systematic significance. Corresponding lower limit is \( z > 0.42 \).

4. REDSHIFT ESTIMATES AND CONCLUSIONS

A primary goal of this exercise is to use the host fluxes to constrain the source redshift, adopting the standard candle hypothesis. To this end, we use the Hubble diagram curve computed in Meisner & Romani (2010). This curve follows an elliptical host formed at \( z = 2 \) and evolving according to the Fioc & Rocca-Volmerange (1997) models to the observed \( z \) in our standard cosmology, computing the observed flux by folding through the \( i' \) filter. However, a recent spectral survey of Fermi BL Lac objects (Shaw et al. 2013b) finds that the host luminosity of these \( \gamma \)-ray sources is 0.4 mag fainter than the \( M_B = -22.9 \pm 0.5 \) reported by Sbarufatti et al. (2005). We thus amend the Hubble diagram by normalizing the evolving models to this decreased luminosity at \( z = 0 \).

Using this curve (Figure 5), we translate the host magnitude values and upper and lower statistical and systematic errors to redshift estimates and error ranges. These are reported in Table 2. When only an upper limit on the flux is available, this translates to a redshift lower limit. The redshift estimates for detected hosts varied from 0.13 to 0.58, with lower limits 0.42–0.93. We consider these limits conservative in the sense that we use the revised (less luminous) standard candle calibration above. However, insofar as some BL Lac objects undoubtedly have substantially sub-luminous hosts, individual sources may indeed appear at lower \( z \).

Shaw et al. (2013b) analyzed high S/N spectra of a large number of Fermi BL Lac objects. In a method parallel to the present imaging host search, they detected or placed limits on the BL Lac object host by measuring the flux of a spectral
component from a standard candle elliptical. After appropriate k correction and slit-loss corrections, these measurements provided host redshift estimates or lower bounds. In addition, sometimes intervening metal line absorption systems were detected. These provide firm, model-independent lower bounds on the host redshift. These spectroscopically allowed ranges and lower bounds are listed in the last column of Table 2. We give here the ranges derived for a standard candle magnitude $M_R = -22.5$ for consistency with our imaging results.

Since in this program we targeted BL Lac objects without known redshift, none of our sources has a spectroscopic $z$ in Shaw et al. (2013b). For the five sources with host detection, two (J0316+0904 and J0543−5532) have imaging redshift estimates consistent with the spectra-derived bounds in that paper; the low significance detection of J1023−4336 is also consistent. Three (J0114+1325, J0115+2519, and J0721+7120) lie at slightly lower $z$ than the spectral lower bound, but are within 3σ, and J0115+2519 is fully consistent with the strict lower limit provided by an intervening absorber. However, since completing this study, Pita et al. (2013) have published new high-quality Very Large Telescope/X-shooter spectra of a number of blazars, including J0543−5532, measured here. For this source, they infer $z = 0.237$ based on a weak Ca II H/K doublet and a Na I absorption line. This redshift, near the lower bound of Shaw et al. (2013b), is well below our imaging estimate, implying a host that is substantially fainter than our standard candle assumption. At this $z$, our measured host flux implies an absolute magnitude $M_R = -21.67^{+0.01}_{-0.01} - 0.01^{+0.01}_{-0.01}, 0.8$ mag (1.7σ) away from our assumed standard candle luminosity. The host absolute magnitude is consistent with, but more accurate than, the spectroscopically estimated value in Pita et al. (2013).

In six cases, we derive lower bounds on the redshift; J1023−4336 may be interpreted as a lower bound of $z > 0.42$. These limits are always more constraining than those extracted from the spectroscopic study. For J0558−7459, our new bound is also stronger than that obtained from the intervening absorption line system. Thus these bounds may be useful in BL Lac object population studies (e.g., Ajello et al. 2014).

With median $f_{host}/f_{nucl} = 0.07$, our sources are very strongly dominated by the non-thermal nuclear core flux. This is in contrast to the Hubble Space Telescope study of Scarpa et al. (2000), where of 69 BL Lac objects with resolved hosts, 37 had $f_{host}/f_{nucl} > 1$. Our large core dominance is similar to that found in Meisner & Romani (2010) and, as noted there, it may be attributed to the fact that these are $\gamma$-ray selected BL Lac objects and thus should have high alignment between the jet axis and the Earth line of sight, increasing the core dominance. In addition, these sources were drawn from the BL Lac objects lacking redshifts even after extensive spectroscopy with 8 m-class facilities (Shaw et al. 2013a, 2013b). Since sources with brighter
hosts allow easier absorption line redshift measurements, the remainder (including the sources studied here) should have especially high core dominance.

In previous studies (Scarpa et al. 2000; Urry et al. 2000; Meisner & Romani 2010), the BL Lac objects were seen to have an excess of faint galactic companions, indicating that they were located in cluster environments and that they may have recent interaction activity. In general, the relatively poor seeing and modest image depth achieved during this project prevented us from identifying very faint companions. For two objects, we did find bright companion galaxies nearby. J0114+1325 had two companions within a 3″ (~20 kpc) radius. These companions were close enough that they overlap significantly with the BL Lac object host wings, making accurate flux measurement difficult. We found their $i'$ magnitudes to be roughly 20.5 and 20.8. J0222+4302 had four surrounding bright companions located 11−12″ (~70 kpc) from the core, with $i'$ magnitudes of 18.9, 19.3, 19.5, and 20.9.

We have detected hosts in the images of 5 out of 11 BL Lac objects, plus one marginal detection. Assuming a standard candle host luminosity, these provided redshift estimates $z = 0.127 - 0.583$ ($z_{\text{med}} = 0.37$). The minimum redshifts for the remainder are also larger than available spectroscopic lower limits and so are useful as well. Perhaps unsurprisingly, our host detections were for four HBL (high spectral peak energy, relatively low luminosity) sources and one intermediate peak source. The other intermediate peak sources and the two LBL (low peak, higher power) sources in our sample yielded only lower limits on $z$; these include the highest limit, $z > 0.93$, in this sample.

When no other redshift estimate is available, these imaging-derived values can be useful for statistical purposes, e.g., in population studies. However, as emphasized by the spectroscopic $z$ recently derived for J0543−5532, the standard candle hypothesis is only statistically useful, at best, and should be subject to further study. Indeed, Pita et al. (2013) estimate that two of their BL Lac object hosts have $M_K < -24$, even further from the expected standard candle value. Our host flux measurements thus remain useful whenever an independent redshift is derived. The prospects for further spectroscopic redshifts of our imaged hosts are, in fact, good. These are excellent targets for spatially resolved spectroscopy, especially with Integral Field Unit feeds, which can isolate host spectral features from the wings of the BL Lac object.

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REFERENCES

Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJ, 743, 171
Ajello, M., Romani, R. W., Gasparrini, D., et al. 2014, ApJ, 780, 73
Caccianiga, A., Maccacaro, T., Wolter, A., Della Ceca, R., & Gioia, I. M. 2002, ApJ, 566, 181
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Marcha, M. J. M., & Caccianiga, A. 2013, MNRAS, 430, 246
Meisner, A. M., & Romani, R. W. 2010, ApJ, 712, 14
Nilsson, K., Pursimo, T., Villforth, C., et al. 2012, A&A, 457, A1
Pita, S., et al. 2013, A&A, in press (arXiv:1311.3809)
Rector, T. A., Stocke, J. T., Perlman, E. S., Morris, S. L., & Gioia, I. M. 2000, AJ, 120, 1626
Sandrinelli, A., Treves, A., Falomo, R., et al. 2013, AJ, 146, 163
Sharafatti, B., Falomo, R., Treves, A., & Kotilainen, J. 2006, A&A, 457, 35
Sharafatti, B., Treves, A., & Falomo, R. 2005, ApJ, 635, 173
Scarpa, R., Urry, C. M., Falomo, R., Pesce, J. E., & Treves, A. 2000, ApJ, 532, 740
Shaw, M. S., Filippenko, A. V., Romani, R. W., Cenko, S. B., & Li, W. 2013a, AJ, 146, 127
Shaw, M. S., Romani, R. W., Cotter, G., et al. 2013b, ApJ, 764, 135
Urry, C. M., Scarpa, R., O’Dowd, M., et al. 2000, ApJ, 532, 816