Journal of the Southeastern Association for Research in Astronomy, **7**, 33-36, 2012 December 1

DETERMINING CELL SIZES IN THE TURBULENT JET OF BLAZAR S5 0716+714

Hannah Rafle[1]
Metropolitan State University of Denver, CO, 80204

and

James R. Webb, and Gopal Bhatta
Department of Physics, Florida International University, FL, 33199

ABSTRACT

In this study we utilize a new model for analyzing microvariability in light curves of the BL Lac object S5 0716+714 in order to determine the size distribution of the turbulent cells within the jet. The model assumes that the microvariations seen in the light curves of blazars are due to a series of pulses caused by a shock wave hitting turbulent cells in the jet. The model fitting program was written in IDL allowing the user to read in the light curve data, and then fit pulses to the curve by modifying three parameters. The pulse determined by the model fit was then converted into cell size in Astronomical Units (AU) and the distribution of cell sizes was determined by compiling the results from fitting the model to 37 separate microvariability curves. This distribution had a minimum of 3.955 AU and a maximum of 79.1 AU with a median of 12.814 AU.The pulse model proved to be a good fit for the light curves of S5 0716+714 with an average correlation coefficient of 0.955.

Subject headings: blazars,quasars, S5 0716+714

1. INTRODUCTION

A blazar is an extremely active galactic nucleus thought to harbor a supermassive black hole that emits primarily through synchrotron emission from an ultra-relativistic jet accelerated out along the rotational axis of the Black hole. The BL Lac object S5 0716+714 is a particularly bright blazar with a high declination and has been widely studied. S5 0716+714 is a good candidate for micro-variability studies as it displays nearly continuous micro-variability activity with a duty cycle of 95.3% (Webb et al. 2010). This object is also well suited to the goals of this study since there is high quality data available which spans many years.

Microvariability, or intranight optical variability (INOV), is defined as changes in a few tenths of a magnitude over a period of less than an hour. Microvariability seen in a blazar light curve can be explained as a non-relativistic shock traveling down a turbulent jet. The shocks are formed by uneven supply of particle and fields at the base of the jet which then propagates down the jet (Marscher et al. 1992). Kirk et al. (1998) analyzed the synchrotron emission for a shock propagating through a cylindrical relativistic jet. They assumed a homogeneous magnetic field with small amounts of magnetic tangling and an inhomogeneous distribution of electrons. The electrons are energized by the shock passing through the region and then cool by synchrotron emission.

The Kirk model applies to only one cylindrical area encompassing the entire jet width, whereas we propose that within a given volume of the jet there is the possibility of multiple "cells" or cylindrical volumes. We assume these turbulent cells represent an enhancement in the density, and or the magnetic field in the cell caused by turbulent eddies forming in the plasma. If the flow is laminar, there are no turbulent cells and thus it cannot produce the microvariability seen in the curves.

2. DATA

Beginning in 1996 and lasting until 2003, Montagni et al. (2006) undertook a long term observational campaign monitoring S5 0716+714. The result was 10,675 individual photometric measurements over 102 nights. The primary filter used was the R filter, but V, B and I filters were also used during some observations. The average duration of the resulting microvariability light curves was approximately 9 hours. The average photometric error for each CCD image was on the order of 0.01 magnitude. In most light curves instrumental noise was the largest uncertainty, but in some data sets the sky noise due to approaching twilight dominated the uncertainty at the ends of the curves. The analysis of Montagni et al. (2006) concentrated on finding time scales for the most rapid INOV. This was accomplished by dividing each curve into intervals so that a linear fit could be used to evaluate the change in magnitude over time($\left|\frac{dm}{dt}\right|$). They concluded that the average $\left|\frac{dm}{dt}\right|$ was about 0.027 mag/h and the probability of finding a variation rate higher than 0.2 mag/h during a single night is smaller than 1 chance in 10^3. This data set was ideal for our study since it was generally of high photometric accuracy and covered multiple years. At the time, this was one of the largest studies undertaken on the any single blazar and remains one of the largest long term studies. The long term nature of the campaign provided a wealth of light curves to use for our project.

3. PROCEDURE

3.1. *Selection of Curves*

For this study, careful selection of light curves was highly important. Although the data set included light curves through the B, V and I filters, we decided to limit

[1] Southeastern Association for Research in Astronomy (SARA) NSF-REU Summer Intern
Electronic address: h.i.rafle@gmail.com

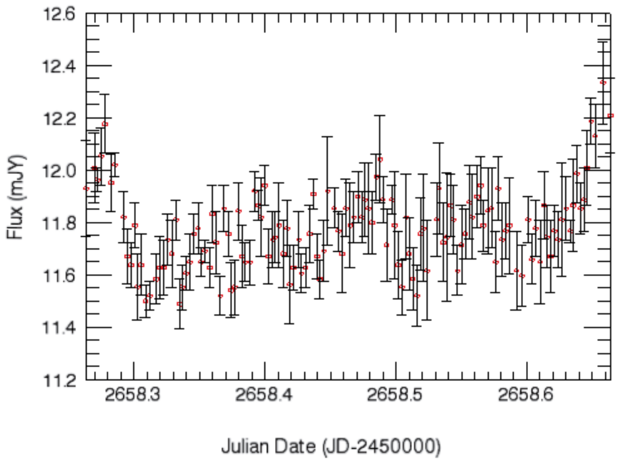

Fig. 1.— Light Curve for 2003 January 18.

our sample to light curves in the R filter. This decision was due to the R light curves being the most numerous in the data set, and because the model had already been solved for characteristic pulses in the R frequency range.

Some of the R light curves were not used if the error for the individual points was larger than $\Delta m \sim 0.01$. Large errors made it difficult to distinguish between noise and actual pulses. Figure 1 is an example of a curve that was too noisy to be fitted. The number of points over the curve was also taken into consideration. Curves which were more sparsely populated tended to be harder to fit as again it was difficult to distinguish between noise and pulses. In general, curves with approximately 100 points over an eight hour period could be used to fit the model pulses. There were exceptions to this criteria, for instance if a curve was of a shorter duration then the "point density" was examined to determine if we could obtain a meaningful model fit. The goal was to avoid fitting low degrees of freedom pulses. In other words, a three parameter model fit had to contain more than five points or it was excluded from the analysis. For most pulses, the degrees of freedom per pulse was greater than 15. For most curves, an initial plot of the magnitudes was enough to determine if that light curve could be used. In summary, we concluded that the light curves had to be in the R filter, contain approximately 100 data points and exhibit evidence of microvariability with small error to be included in the study.

3.2. *IDL Programs*

The reduced data was obtained in a spreadsheet format with calendar dates, magnitudes and error. For our program, we needed to convert calendar dates to Julian dates and magnitude to flux which was done by IDL programs. It was also necessary to make some modifications to the IDL code that generated the model fit. The original code input was for a single multiwavelength file. We altered the code to accept a single filter with different file lengths. Additional modifications were made so the program could be run multiple times with relative ease.

3.3. *Pulse Profile*

The pulse profile that we fit to the observations was computed following Kirk et al. (1998). Bhatta et al. (2012) solved the hydrodynamic equations describing the acceleration of a distribution of electrons by a strong shock and the subsequent synchrotron cooling. We assume that the particle acceleration timescale is equal to one half the particle escape timescale, $\tau_{acc} = \frac{1}{2}\tau_{esc}$ in the model. The pulse shapes were solved at a center frequency of $\nu = 4.3 \times 10^{14} Hz$ (R-band). In fitting a pulse to the data, there were three variables that could be set: the center, the amplitude, and the width. The center of the pulse corresponds to the physical location of the turbulent cell within the jet. The amplitude for the pulse is a measure of the density enhancement or magnetic amplification in the cell presumably due to turbulence. Finally, the width of the pulse measures the duration of the flare and is related to the size of the turbulent cell. Since the velocity of the shockwave is assumed in the model to be $0.1c$ relative to the jet material, it is possible to determine the physical size of the cell from by determining width of the individual pulse.

3.4. *Fitting*

We began the fitting process by estimating the number of pulses based on inspection of the lightcurve and estimating the centers, amplitudes and widths of the initial pulses. The program then calculated the resulting model and computed the Pearson correlation coefficient between the data and the model for the initial fit. The three model parameters were then fine tuned until we obtained the maximum correlation coefficient. Most correlation coefficients were well over 0.9. Most pulses were highly convolved so that adjusting the amplitude or pulse width of one pulse affected the fit of an adjacent pulse. This indeed complicated the fitting process, but even the most highly convolved light curve could be maximally fit in a three or four hour period with educated parameter adjustment. Subsequent versions of the fitting program will be automated, but due to the short length of the summer, this feature was not available for this work.

We found there was a "critical number" of pulses specific to each curve. If this number was exceeded, then it became difficult to accurately fit the curve and the resulting correlation coefficient decreased dramatically. When the extra pulse was removed, the model fit the data much better and the correlation coefficient increased. The apparent pulse was actually due to noise rather than true micro-variability activity. In the cases where it is difficult to establish a fit for the pulse there were usually large error bars. Figure 2 is an example of an extremely good light curve with the model fit to it. The data is in red with error bars and the blue line is the fit for the model. It consists of 11 well defined pulses. Figure 3 is the model plotted on the same axes for comparison. To check how well the model fit the specific light curve we calculated the Pearson correlation coefficient by comparing the raw data to the model and the curve in Figure 2. The resulting fit has a Pearson correlation coefficient of 0.95 with 124 degrees of freedom.

Thirty-seven individual light curves were fit from 1999 January 5 1999 to 2003 March 23. These 37 light curves had a combined observation time of 333.12 hours. The

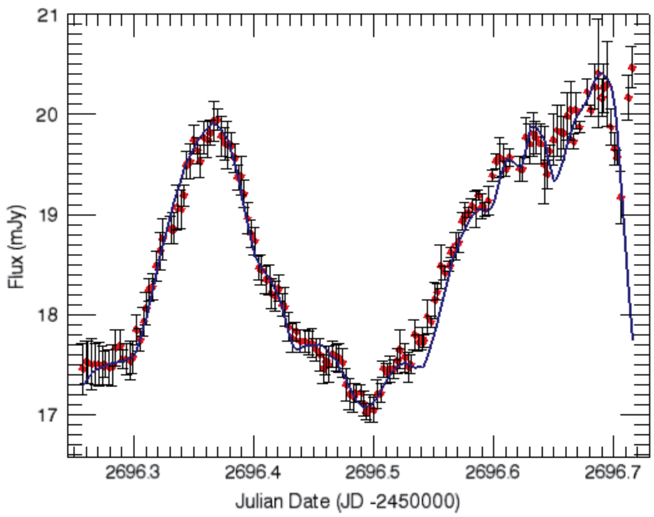

Fig. 2.— The light curve for 2003 February 25 with the model fit superimposed. The resulting fit has a correlation coefficient of 0.95 with 124 degrees of freedom.

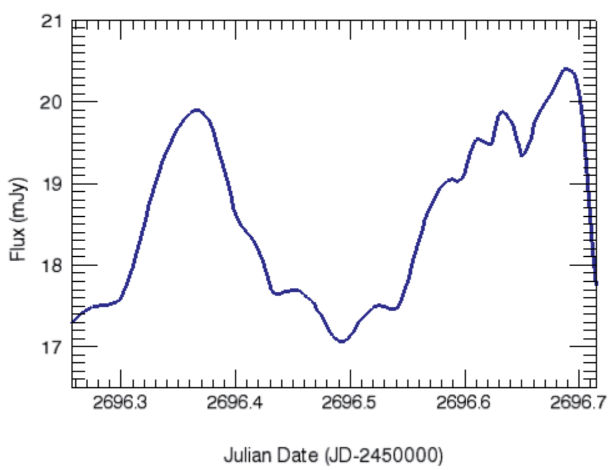

Fig. 3.— The model for 2003 February 25.

average duration of each light curve was 9 hours. The average correlation coefficient of the standard pulse fit was 0.955 with a maximum of 0.997 and a minimum of 0.85. Table 1 shows the values for each curve. The 37 light curves produced a cumulative 231 pulses.

4. INTERPRETATION

One of the aims of this project was to determine the distribution of the cell sizes and compare them to what we expect from eddies resulting from turbulence in a plasma jet. This distribution could be determined by determining the duration of all of the individual pulses and factoring in the shock speed (assumed to be 0.1c as mentioned above in the pulse profile section). Figure 4 shows a distribution of the cell sizes we found by analyzing the data presented here. The cell sizes are centered around 7.754 AU and are more or less a continuous distribution

TABLE 1
Fitted light curves

JD	Points	Pulses	Corr. Coeff	Deg. of Freedom
2451183.5	96	6	0.97	78
2451623.5	126	3	0.97	117
2451624.5	106	5	0.93	91
2451845.5	97	5	0.98	82
2451882.5	117	4	0.99	105
2451923.5	146	6	0.97	128
2451954.5	146	5	0.96	131
2451966.5	146	8	0.99	122
2452027.5	94	8	0.99	70
2452147.5	92	7	0.94	71
2452193.5	108	6	0.97	90
2452216.5	139	8	0.97	115
2452306.5	114	6	0.96	96
2452307.5	156	5	0.88	141
2452308.5	129	5	0.90	114
2452334.5	116	4	0.98	104
2452348.5	130	4	0.97	118
2452353.5	126	3	0.97	117
2452358.5	123	6	0.93	105
2452365.5	122	5	0.95	107
2452385.5	95	6	0.94	77
2452386.5	107	8	0.94	83
2452395.5	101	6	0.94	83
2452575.5	110	6	0.92	92
2452576.5	129	6	0.85	111
2452582.5	133	8	0.94	109
2452584.5	67	4	0.97	55
2452665.5	153	5	0.93	138
2452679.5	138	8	0.95	114
2452680.5	149	5	0.96	134
2452688.5	159	12	0.97	123
2452694.5	85	7	0.95	64
2452695.5	157	11	0.95	124
2452702.5	138	4	0.99	126
2452716.5	115	9	0.95	88
2452720.5	123	6	0.96	105
2452721.5	125	7	0.96	104

consistent with our assumption that the cells are due to turbulence in the jet flow. Most of the cells are at smaller sizes, also consistent with what is expected from turbulence. We compared our results to those of (Bhatta et al. 2012) who analyzed a continuous 72-hour light curve of this same object using the identical model and found our results are remarkably consistent with that much longer continuous light curve.

We were also interested in determining the minimum cell size since that would correspond to the Kolomogrov scale for turbulence. To compute this, we calculated the theoretical minimum which we defined by three points; a base, where the flare begins, a peak, and a second base where the flare ends. In this data, the minimum exposure time was two minutes (Montagni et al. 2006) therefore the minimum would be 6 minutes. The "pulse" duration was converted into AU using the shock speed and the resulting theoretical size is 0.592 AU. The actual minimum pulse width seen in the data is 3.955AU, more than 6.68 times greater than the theoretical minimum. This large gap between an absolute theoretical minimum and the actual observed minimum gives us confidence that we have found the minimum for this data set. In plasma theory, the Kolomogrov size-scale is directly related to the physical conditions in the jet. Outliers in the cell sizes distribution can be seen in Figure 4. These large cells only appeared in a couple of the light curves. There

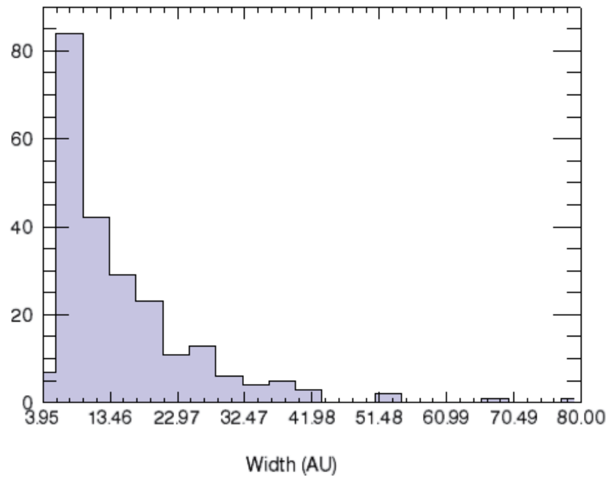

Fig. 4.— Distribution of cell sizes

are also large gaps between these outliers and the rest of the data. There are a few possible explanations for this. The first is that these size cells are less common but not unusual and with more data points they would cease to be outliers. The second explanation is these outliers are not a single cells, but rather very highly convolved set of smaller cells that we cannot separate due to the noise in the data. We need more data with better signal-to-noise to see which is the more likely scenario. Although it is beyond the scope of the current paper, this result can be used in the future to further establish estimates on the viscosity and the nature of the plasma flow in these jets.

5. CONCLUSION

In this study a new model to explain microvariability was tested by fitting 37 light curves of the Blazar S5 0716+714. These light curves spanned from January 2009 January 5 to 2003 March 23. We found that the model proved to be an good fit for the light curves of 0716+714. The model in turn provided information on the size of turbulent cells within the jet. A distribution of the sizes of the cells was obtained. For this data set, the cell sizes ranged from 3.955 AU to 79.1 AU with a median of 12.814 AU and we associated the smaller length-scale to the Kolomogrov size-scale in the turbulent plasma.

5.1. *Future Progress*

Both this study and the Bhatta study were for a single color which can only provide a limited amount of information about blazar jets. A multicolor study would prove beneficial. Carini et al. (2011) performed simultaneous observations of 0716+714 in the B and I filter in March 2003 and did hysteresis analysis. Although they did note the presence of microvariability in the curves they chose to treat the whole night as one pulse. When comparing the dates of the two studies we found our study concluded the day before Carini et al. (2011) started their observations. In our data we found clearly defined pulses and similar behavior also appears in the Carini data. As a result it might be possible to better resolve the hysteresis loops by first deconvolving the pulses with our pulse model and then constructing hysteresis loops for individual pulses.In addition to gathering more data for this object, much more analysis can be done with this model. At present time the model has only been tested on S5 0716+714, but there are many other blazars which display consistent microvariability. Fitting the model to light curves from other Blazars is the next logical step in this process.

6. ACKNOWLEDGMENTS

This project was funded by the National Science Foundation Research Experiences for Undergraduates (REU) program through grant NSF AST-1004872. I would like to thank FIU graduate student S. Dhalla for her advice and support throughout this project. My sincere thanks also goes to F. Montagni and his team for use of their data for this project. I would also like to thank Dr Martha Leake, professor of Physics (and Astronomy) at Valdosta State University for her guidance at Kitt Peak National Observatory.

REFERENCES

Bhatta, G., et al. 2012, A&A, submitted
Carini, M. T., Walters, R., & Hopper, L. 2011, AJ, 141, 49
Kirk, J. G., Rieger, F. M., & Mastichiadis, A. 1998, A&A, 333, 452
Marscher, A.P. Gear, W.K., & Travis, J.P. in Variability of Blazars (E Valtaoja, M Valtonen eds.) Cambridge Univ. Press, 85
Montagni, F., Maselli, A., Massaro, E., Nesci, E., Sclavi, S. & Maesano, M. 2006, A&A, 451, 435
Webb, J. R., Bhatta, G., & Hollingsworth, H. 2010, AAS Meeting Abstracts, 216, #420.11