WAVELET ANALYSIS OF MICROVARIABILITY IN BLAZARS 0716+714, ON231 AND BL LAC

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ABSTRACT
Wavelet analysis is applied to the microvariability light curves of blazars 0716+714, ON231 and BL Lac. We analyzed 13 microvariability light curves and determined the two most powerful periods for each data set using the IDL wavelet toolkit. Periods were compared between data sets to identify trends. Relativistic cosmological and beaming effects were used to determine the periods in the rest frame of the objects. These periods were then used to draw conclusions about the physical conditions in the relativistic jet. We interpret the flux variations in terms of collective plasma processes in the jets. From our analysis, inhomogeneities in the ambient jet medium are a length scales of $10^{15}$ meters.

Subject headings: blazar: general — blazar: individual (0716+714, ON231, BL Lac) — blazar: microvariability — wavelet: application

1. INTRODUCTION
An Active Galactic Nuclei (AGN) is a type of object that is extremely distant from earth and as such has many unknown properties. However, it has been well established that at the center of an AGN there is a super massive black hole. A super massive black hole is an object that is up to $10^9$ times the mass of the sun and is compacted to an extremely small size due to an intense gravitational field. This black hole is rotating and is ideally located in the sky for observations most of the year. The observations of 0716+714 were made at the Dark Sky Observatory (DSO) by J.T. Pollock. These three objects were chosen because they have demonstrated variability on all timescales and are known to have shown microvariability in their light curves. For this study, the main selection criteria were:

- if the object has previously shown microvariability,
- the length of the data sets are long (≥ 5 hours was ideal)
- multiple data sets were available for the same object on different dates (except ON 231)
- the quality of the photometry was excellent so the microvariations were well above the noise.

Table 1 gives pertinent information on each of the objects selected for this study. Column 1 gives the common name, while columns 2 and 3 give the location and column 4 lists the redshift. Column 5 indicates the reddening value used to reduce...
TABLE 1

OBJECT INFORMATION

<table>
<thead>
<tr>
<th>name</th>
<th>RA</th>
<th>Dec</th>
<th>z</th>
<th>E(B-V)</th>
<th>(\delta^b)</th>
<th>classification</th>
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</thead>
<tbody>
<tr>
<td>0716+714</td>
<td>7:21:53.4</td>
<td>71:20:36</td>
<td>0.30</td>
<td>0.031</td>
<td>9.56</td>
<td>HPQ, BLLAC</td>
</tr>
<tr>
<td>ON231</td>
<td>12:21:31.7</td>
<td>28:13:59</td>
<td>0.10</td>
<td>0.023</td>
<td>1.5</td>
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</tr>
<tr>
<td>BL Lac</td>
<td>22:02:43.3</td>
<td>42:16:40</td>
<td>0.07</td>
<td>0.329</td>
<td>3.8</td>
<td>BLLAC</td>
</tr>
</tbody>
</table>

NOTE. — data obtained from NASA/IPAC Extragalactic Database (NED)

\(^a\)High polarization quasar
\(^b\)0716+714 from Downs et al. (2006), ON231 and BL Lac from Jiang et al. (1997)

TABLE 2

MICROVARIABILITY OBSERVATION DATA

<table>
<thead>
<tr>
<th>object</th>
<th>date</th>
<th>index #</th>
<th>duration (hrs)</th>
<th>telescope</th>
<th>exposure time (sec)</th>
<th>reduction program</th>
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</thead>
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<td>1</td>
<td>5</td>
<td>DSO</td>
<td>200</td>
<td>MIRA</td>
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<td>200</td>
<td>MIRA</td>
</tr>
<tr>
<td>0716+714</td>
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<td>8.7</td>
<td>DSO</td>
<td>200</td>
<td>MIRA</td>
</tr>
<tr>
<td>0716+714</td>
<td>11/13/2004</td>
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<td>9.3</td>
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<td>200</td>
<td>MIRA</td>
</tr>
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<td>0716+714</td>
<td>2/17/2005</td>
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<td>10.8</td>
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<td>ON231</td>
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<td>SARA</td>
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<tr>
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<td>13</td>
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<td>SARA</td>
<td>200</td>
<td>MIRA</td>
</tr>
</tbody>
</table>

the photometry and column 6 lists the relativistic Doppler factor from the literature used to convert the luminosity to the \(\tilde{\Sigma}\)et rest frame. The final column lists the classifications.

2.2. Photometry

The equipment used at Dark Sky Observatory (DSO), located in Northwestern corner of North Carolina and run by Appalachian State University, was the 0.81 m f/13 Cassegrain telescope which uses a Photometrics CH 250 camera. All data from 0716+714 were taken using the R band filter. Images of ON231 were also obtained from J.T Pollock. The South- eastern Association of Research in Astronomy (SARA) 0.9 m telescope at Kitt Peak, AZ was used to obtain images of BL Lac. The data images for this study were reduced using MIRA. Several BL Lac curves showed erratic comparison star deviations and had to be re-reduced because of a problem in the cosmic ray filter. When the cosmic ray filter was applied to these images in the first photometry session, it created holes within the stellar images which affected the magnitude. We re-reduced the original images and the cosmic ray filter was used to a minimal extent. This eliminated the holes in the objects and yielded much improved photometry. Table 2 lists the relevant details of the observations we analyzed including the dates of the observations (column 2), the duration of the microvariability runs (column 4), and the exposure times for each image (column 6).

2.3. Time Series Analysis techniques

The study of brightness variability in these jets over time can be studied using timescale analysis. The traditional way to determine timescales is to use a Fourier transform. The Fourier transform essentially fits sine waves of varying frequencies and amplitudes to a data set and determines how well the sine wave follows the data set. The Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) were used in previous studies (Wilkat et al. (2002); Downs et al. (2006)) to model blazar microvariability. A more mathematically complicated and possibly accurate model is known as a wavelet. Wavelets are similar to plane wave fitting routines, except they are not plane waves, but spatially isolated “wavelets”. The wavelet is scaled in time to the length of the time series and fit in frequency, amplitude and time. Thus, to represent a wavelet, you need three axes, period (frequency), time and power.

Essentially a wavelet function is used to divide an input signal into its varying frequency components. Because of this functionality, the wavelet is extremely useful for data sets that have discontinuities or sharp peaks much like the microvariability that is analyzed in this study. This wavelet model is the result of applying a small wavelet function over a data set and using a scaling function. There are many different wavelet families each of which contains a different type of wavelet function. For example, a Morlet wavelet function (Goupillaid et al. (1984)) with an order of six appears in Figure 1. This small wavelet is then applied to the data set utilizing varying periods and amplitudes to determine the period of best fit.

We used two programs written in the IDL: the IDL wavelet toolkit and a wavelet program written by Torrence and Compo (available at URL: http://paos.colorado.edu/research/wavelets/). The wavelet program allows the user to import data into the program and then shows the resulting wavelet in a two-dimensional graph. This graph shows the time on the x-axis and the period on the y-axis. A color scale is used to show power or the periods at which the wavelet function had a high correspondence to the data set imported (highest power). Similarly, the wavelet toolkit allows the user to import data sets and plots the wavelet power spectrum in three-dimensions allowing the
user to view the z-axis both physically and through a sliding color scale. The toolkit also allows the user to change the wavelet family and order with a simple click. The user can also change the appearance of the wavelet model or display significance levels up to the 99.9% level. On the far right side of the active window which displays the model, the mean power value of a particular period is displayed which allows easy identification of the most relevant period. We tested the wavelet method by applying the wavelet analysis to sine waves generated in order to learn how to interpret the resulting wavelet spectrum. In order to enhance the understanding of the wavelet spectrum, the following were used: Figure 2 shows the wavelet power spectrum of random noise with the same amplitudes as our light curves. None of the features of the wavelet power spectrum were significantly above the 99% significance surface. The x-axis is the time axis in arbitrary time units, while the y-axis is the scale axis, or period axis. The z-axis is the power of the wavelet with a particular scale at a particular time. It is also color-coded for easier interpretation of the power. Note the panel at the rear of the diagram is the actual light curve analyzed (hidden in this Figure by the confidence sheet) and the left panel is the integrated power as a function of scale.

Similarly, we generated pure sine waves, and sine waves with noise added. The wavelet could easily distinguish identify the sine function even if the noise was significant. Figure 3 shows the wavelet spectrum of a sine wave with a modest amount of noise added. The axes are the same as in Figure 1. Note the 99% contour sheet is well below the signal.

2.4. Data Reduction

The original light curve data sets were imported into the two IDL programs in the format of hours vs. magnitude (or flux in the case of 0716+714). The wavelets that were generated showed a strong linear trend which denoted the long-term variability which was not an aspect of this study. In order to study the microvariations the long-term variability needed to be removed. This was accomplished by removing the linear trend from the individual data sets.

All of the wavelets generated showed at least one very strong period that was well above the 95% significance level and, in most cases, above the 99% significance level. As shown in the sample sine waves, any period that was above this significance level was important to the data set that was being analyzed. In both of the programs used, there was originally no way to print out the numerical values of the models used to plot the wavelet. In order to recover the numerical values we wrote an IDL wave output program that extracted the data plotted by the wavelet programs. The program also searches for the maximum power and selects out that power and its corresponding period and time values. All of this is saved to a file which is defined by the user. The maximum power, with the corresponding time and period components, is printed at the top of the document. After this program was written, all of the data points within either program could be printed out and saved to a file. When the program was used and compared to the data sets of 0716+714, it was noticed that the wavelet toolkit performs a conversion between the true period that is represented on the graph and scaled periods that are actually stored in the program. The transformation between these values was not given and even the techs at IDL
TABLE 3  
PERIODICITY DATA FOR OBJECTS 0716+714, ON231, BL Lac

<table>
<thead>
<tr>
<th>index #</th>
<th>1st period (hrs)</th>
<th>2nd period (hrs)</th>
<th>max power</th>
<th>comp perioda</th>
<th>comp period</th>
<th>luminosity [log(ergs/sec)]</th>
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</thead>
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<td>0.000892</td>
<td>1.42</td>
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<td>2.79</td>
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<td>1.37</td>
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<td>0.00157</td>
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<td>0.000609</td>
<td>1.37</td>
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<td>30.18</td>
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<tr>
<td>13</td>
<td>0.830</td>
<td>1.97</td>
<td>0.00623</td>
<td>0.907</td>
<td>2.23</td>
<td>30.34</td>
</tr>
</tbody>
</table>

aComparison values obtained from Wilkat et al. (2002) and Downs et al. (2006) from Fourier transforms

bIndex numbers 6,7,8,10,11,12,13 were compared to other data sets from the same object as these data sets have not been previously analyzed.

did not know. Thus, we determined the correct conversions for the Morlet wavelet case as:

\[
\tau = 2^{\tau_{max} - \tau_{given} + 1})\delta t
\]  (1)

with \(\tau_{max}\) the maximum period value printed out, \(\tau_{given}\) the scaled period value and \(\delta t\) the time step used as explained below. \(\tau\) is the correct period as graphed. We also identified a bug in the wavelet toolkit, and with the IDL support center’s help, corrected the pointer in the lower left corner so that it correctly displayed the time, period and power values for a specific cursor location.

3. RESULTS

3.1. Wavelet Analysis Results

By using the maximum power from the wave output program, the two strongest periods for each data set in each program was determined. First all of the dominant periods obtained for a specific data set were analyzed. Both programs rely on a value of \(\delta t\), or the change in time between steps, to graph the wavelet. Since the program knows the number of data points input it averages a value for \(\delta t\) then uses these values instead of the input time values. However, the two programs use a different value of \(\delta t\) which means that when the periods are compared between the two programs, slight discrepancies resulted. In most cases, the data obtained fits within the margin of error expected due to the different values of \(\delta t\). All four period values were compared for each specific data set. These usually aligned fairly well. For example, if one program showed only one dominant period, so did the other program. The wavelets generated separately by the two programs looked extremely similar. We then expanded this comparison to all of the data sets of the same object. This step allowed for the identification of any frequently determined periods. If a period occurred frequently over the span of days, months or years, this indicates a significant period. Ultimately, these periods may be related to processes occurring within the jets. One of the final steps for data analysis involved comparing the maximum periods obtained from all of the data sets combined. In order to do this Table 3 was constructed and then searched for similar trends.

3.2. Object Comparison

When all of the data sets were compared, there appeared to be some trends between objects. In four out of the eight data sets for 0716+714 there was a period of approximately 5.5 hours. A period was found in ON231 at slightly over 3 hours. Also, in BL Lac, three of the data sets contained a period around 1.5 hours.

We have included only wavelet toolkit images in this paper since they are much more easily interpreted than the 2-d plots. The plots are interpreted as described above.

3.3. 0716+714

The majority of the data sets from 0716+714 were longer than 9 hours with the single exception of index number one which was only 5 hours in duration. This means that any period found that was 9 hours or greater would simply correspond to the linear trend in the data set. Since all of the data sets had the linear trend removed, this should not be in issue and instead any strong periods should result from the actual microvariations.

The most frequently occurring period was around 5.5 hours. A period within the range of 0.5 hour of this frequent period was observed in six out of the eight data sets for 0716+714. This was evident in many of the wavelet transforms and for illustration, please examine the Figure 4.

FIG. 4.—Data Set 53075, index number 4, (axes are the same as in Figure 2)
TABLE 4
RELATIVISTIC PERIODICITY DATA FOR OBJECTS 0716+714, ON231, BL Lac

<table>
<thead>
<tr>
<th>index #</th>
<th>1st period obs (hrs)</th>
<th>2nd period obs (hrs)</th>
<th>1st period source (hrs)</th>
<th>2nd period source (hrs)</th>
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<td>7.01</td>
<td></td>
</tr>
</tbody>
</table>

On this image the pink sheet was the 99% significance level. As observed, there was a large portion of the curve above this level which would imply that there was more to the signal than noise. Although edge effects are important in interpreting time series analysis with short time series duration, the removal of linear trend adds significance to this period since it removes whatever strong DC component that might affect long periods. Also due to the nature of wavelets, the wavelet diagram illustrates the importance of edge effects by noting the shape of the power distribution as a function of the time coordinate. A clear representation of these effects can be seen in Figure 3 where the sine curve propagates throughout the data, but the power peaks in the center where the edge effects are minimized.

Another significant period occurred around 3.5 hours. In four out of the eight data sets, this period was high above the significance level. Since this period was drastically shorter than the length of all of the data sets used for this object, it was likely to be a very significant period. A final common period occurred around 7 hours in most of the longer data sets. This period was in four out of the eight data sets. To determine the significance of this period more fully, longer data sets would be required.

3.4. ON231

This data set was about 8 hours long and a strong period of approximately 3 hours was found. Unlike all of the other wavelets, this data set still contained the linear trend because it did not effect the wavelet power spectrum. As evident in the original light curve which was projected against the back of the figure 5, there were strong oscillations in the data. The scale was in Julian date instead of hours on the plots visual, but for analysis was converted to hours in order to compare with the other data sets. The pink sheet shown was the significance at 99.9% which maintains all of the detail to the wavelet.

3.5. BL Lac

Four data sets of this object were analyzed. In each of the data sets there was a period around 1.5 hours. This period was dominant in both wavelet programs and was significant above the 99% level. Since the shortest data set for BL Lac is 3.5 hours, this means that the frequently appearing period was not effected by the length of the data set. A wavelet for BL Lac is shown in Figure 6.

This image shows a 95% significance sheet but if this were to be increased to 99% the peaks still would remain above the significance level.

4. INTERPRETATION

Since blazars are distant objects and synchrotron radiation is emitted by plasma movement at a significant portion of the speed of light, relativistic effects must be calculated. Values for the doppler beaming factors were obtained from previous studies and were referenced in Table 1. The equation used to
find the doppler beaming factor was

$$\delta = \frac{1}{\gamma(1 - \beta \cos \theta)}$$ \hspace{1cm} (2)

where

$$\beta = \frac{v}{c}$$ \hspace{1cm} (3)

and

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$ \hspace{1cm} (4)

In order to convert from the observed period to the relativistic period, the following equation was used

$$\Delta \tau = \frac{\Delta \tau_{\text{obs}}}{1 + \frac{v^2}{c^2}} \delta$$ \hspace{1cm} (5)

Where $\theta$ was the angle observed to the object, $v$ was the speed of the synchrotron radiation, $c$ was the speed of light, $\Delta \tau$ was the relativistic period, $\Delta \tau_{\text{obs}}$ was the observed period and $z$ was the redshift from table 1. Using these equations, the rest frame periods in Table 4 were determined. The relativistic periods were longer than the observed periods due to the relativistic corrections.

Relativistic jets are composed of plasma and therefore can be analyzed using plasma processes. Collective emission is a process that can occur when an electron beam propagates through plasma. As discussed in Benford (1991), collective emission is important when the ratio of densities $\eta_{\text{beam}}/\eta_{\text{plasma}}$ exceeds 0.01. Once this limit is reached, the collective emission significantly overpowers the synchrotron emission of a single particle.

Benford interpreted the rapid variations in 0917+624 as “flux enhancements” due to this process. As the electron beam encounters a lower density region in the ambient plasma, collective processes form “cavitons” which then radiate collectively. Synchrotron radiation controls the energy output at lower density ratios and should correspond to the minimum of the data set. The cavitons are clumps of particles which move in unison and oscillate as a unit. As the cavitons enter a higher density region the collective processes become less important. We can use the microvariations to estimate the length of the rarefied region by equation 4 and

$$d = \sqrt{\frac{\tau_{\text{source}}}{c}}$$ \hspace{1cm} (6)

where $d$ is the length of the region and $v$ is the velocity as determined from $\beta$. Table 5 shows the result of this calculation when $\gamma$ is known. Since collective processes could cause brightness fluctuations, the max luminosity of a data set would correspond to the maximum power due to collective emission. The luminosity amplitude was found by calculating the difference between a local maxima and minima in units of Log(ergs/sec). After taking the inverse logarithm of this value, the power increase between synchrotron radiation and collective emission can be calculated. If this value is greater than 1, it implies that the density ratio is $\geq 0.01$.

As shown in the table, the velocity is very near the speed of light which verifies the significance of the assumed relativistic effects. Using this velocity, the approximate length of the low density region can be calculated using equation 6. In 0716+714 the range of length for this low density region was between $1.01 \times 10^{13}$ meters and $5.69 \times 10^{13}$ m. For ON 231 the length was calculated to be $3.69 \times 10^{13}$ m. The range was more varied for BL Lac with the shortest length being $3.13 \times 10^{12}$ m and the longest $1.38 \times 10^{13}$ m.

### 5. Conclusions

After applying wavelet analysis on 13 data sets obtained from three different blazars, we found some possible periodicities. These periodicities could be attributed to plasma processes that occurred within the relativistic jets. One possible interpretation of the microvariations observed can be attributed to collective plasma emission. This assumes a low density region within the jet that the beam occasionally propagates through and causes the observed microvariations. In our calculations, it appears that this low density is about 200 AU or about the size of our solar system.

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