

## Periodic radio variability in NRAO 530: phase dispersion minimization analysis

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**Abstract** A periodicity analysis of the radio light curves of the blazar NRAO 530 at 14.5, 8.0, and 4.8 GHz is presented employing an improved phase dispersion minimization technique. The result, which shows two persistent periodic components of  $\sim 6$  and  $\sim 10$  yr at all three frequencies, is consistent with the results obtained with the Lomb-Scargle periodogram and weighted wavelet Z-transform algorithms. The reliability of the derived periodicities is confirmed by the Monte Carlo numerical simulations which show a high statistical confidence. (Quasi-)Periodic fluctuations of the radio luminosity of NRAO 530 might be associated with the oscillations of the accretion disk triggered by hydrodynamic instabilities of the accreted flow.

**Key words:** methods: statistical — galaxies: active — galaxies: quasar: individual: NRAO 530

### 1 INTRODUCTION

Active Galactic Nuclei (AGNs) are the most luminous objects in the Universe, and understanding the AGN phenomenon is an important issue in modern astrophysics. The energy production process of AGNs is one of the fundamental problems to be solved in extragalactic astrophysical studies. Currently, direct imaging of the central engines of AGNs is still constrained by insufficient resolution. However, the studies of variability of AGNs and the radiation spectrum are not limited by two-dimensional mapping resolution. Blazars constitute a sub-class of the large family of AGNs, which are characterized by rapid and violent time variability across almost the whole spectrum, high polarization, and compact relativistic jets beaming toward the observers. Some blazars have been found to display periodic or quasi-periodic variabilities in their continuum emission (e.g., OJ 287: Sillanpaa et al. 1988). Periodicity in light curves of blazars is intimately associated with the dynamical process occurring in the central engine of the active nuclei. One can obtain rich information about the internal structure (as well as the variation) and the energy production process from periodicity analysis (Ulrich et al. 1997). However, the complexity in the origins of variability, the interplay of

different variability modes, and the lack of time coverage of the monitoring data make the identification of genuine periods difficult (Fan et al. 2001). Therefore, a well-sampled light curve covering a sufficiently long time span and an accurate and efficient analysis technique are of particular importance for identifying the periodicity of blazars with a time scale of a few years.

Traditional numerical methods used for searching for and identifying periodic fluctuations in time series are based on a Fourier transform (Lomb 1976; Scargle 1981, 1982, 1989). It works well when the signals simply have sinusoidal shapes and the periodicity parameters (such as characteristic frequency and phase) remain constant over the whole time span. However, a real blazar light curve is often a mixture of periodic signals of different time scales, and is always blended with intermittent or short-lifetime flares which cannot be expressed with simple sinusoidal functions in the time domain. In addition, irregular gaps in the monitoring data, non-sinusoidal variations, and other problems would make Fourier techniques unusable and yield misleading results. By contrast, phase dispersion minimization (PDM) is a good algorithm for periodicity analysis of time series with non-sinusoidal oscillation functions and irregular sampling (Stellingwerf 1978; Linnell Nemec & Nemec 1985; Schwarzenberg-Czerny 1989, 1997). Compared to a Fourier-based algorithm, PDM has the advantages in computing speed, implementation efficiency, and statistical confidence, especially in distinguishing true periodic signals from noise.

In this paper, we search for periodicity in the radio light curves of the blazar NRAO 530, making use of the PDM technique. The blazar NRAO 530 (also named PKS 1730–130) is a well-known optically violent variable (OVV) quasar at a redshift of 0.902 (Junkkarinen 1984). It exhibits prominent variability across the whole electromagnetic spectrum covering the radio, optical, ultraviolet, X-ray and  $\gamma$ -ray bands (Hong et al. 2008). NRAO 530 is one of the few blazars showing persistent quasi-periodicity over a time scale of a few years (Hovatta et al. 2008; An et al. 2012) and is a good candidate for investigating long-term periodic variabilities and their associated physical processes. The remaining text is organized as follows: Section 2 describes the radio monitoring data of NRAO 530 used for this analysis; Section 3 introduces the basic principle of the PDM algorithm, and presents the periodicity analysis results, and tests the statistical confidence of the periods using Monte Carlo simulations; a comparison of the results from PDM with other techniques is presented in Section 4; a summary and the conclusion are given in Section 5.

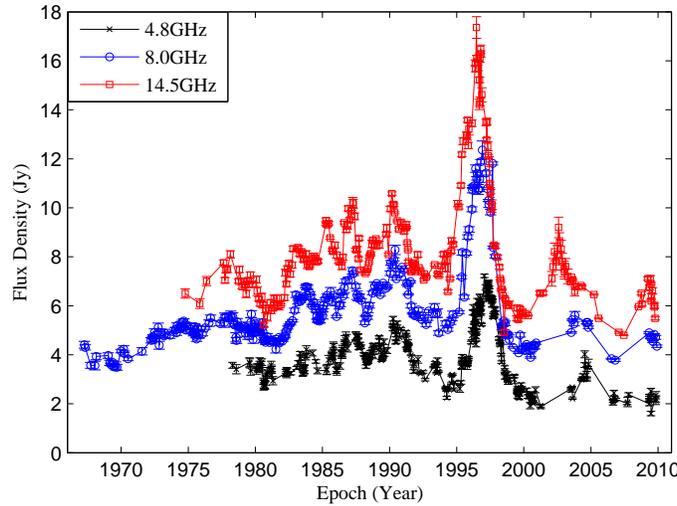
## 2 THE DATA

The total flux density data of NRAO 530 were observed by using the 26-meter radio telescope at the University of Michigan Radio Astronomical Observatory (Aller et al. 1985) at three frequencies of 14.5, 8.0 and 4.8 GHz. The earliest epochs of the observational data in each case were on 1978 April 1 (4.8 GHz), 1967 April 19 (8.0 GHz) and 1974 October 10 (14.5 GHz), respectively. The latest epoch was in November 2009 for all three frequencies. The maximum length of the time span was about 35 yr, which is sufficiently long to search for any quasi-periodicity in the light curves with a few complete cycles. Considering that the time scale of radio outbursts can be from a few months to years, the bi-weekly time sampling is good enough for performing accurate periodicity analysis. The light curves at three frequencies are displayed in Figure 1.

## 3 PERIODIC VARIABILITY OF NRAO 530 USING THE PDM METHOD

### 3.1 The Basic Principle of PDM

The PDM method is a widely used numerical technique to search for and identify periodic fluctuations of the luminosity of variable stars and other astronomical objects (Stellingwerf 1978). In the PDM algorithm, the time series data  $\{(x_i, t_i)\}$  are divided into a number of phase bins, where  $x_i$  is amplitude of the  $i$ th data point at the observing time  $t_i$ . Let  $N$  be the total number of data points and  $M$  be the number of phase bins, and let  $x_{kj}$  represent the  $k$ th data point in the  $j$ th



**Fig. 1** Light curves of NRAO 530 at three frequencies of 14.5 (red square; color online), 8.0 (blue circle) and 4.8 GHz (black cross). In order to avoid the overlapping of data points, the 4.8-GHz light curve has been moved downward by 2 Jy, and the 14.5-GHz flux density has been moved upward by 2 Jy. A major outburst is clearly seen in 1996–1997.

phase bin. A proper  $M$  is chosen according to the trial period, so that for a given trial period  $\Pi$ , the data points in each phase bin have similar phases. The phase of the  $i$ th data point is denoted as  $\phi_i = t_i/\Pi - [t_i/\Pi]$ ,  $i = 1, \dots, N$ ,  $\phi_i \in [0, 1]$ . The bins can overlap to improve the phase coverage, if necessary. The variance  $\sigma^2$  of the whole data set is expressed as

$$\sigma^2 = \frac{\sum (x_i - \bar{x})^2}{N - 1}, \quad (i = 1, \dots, N). \quad (1)$$

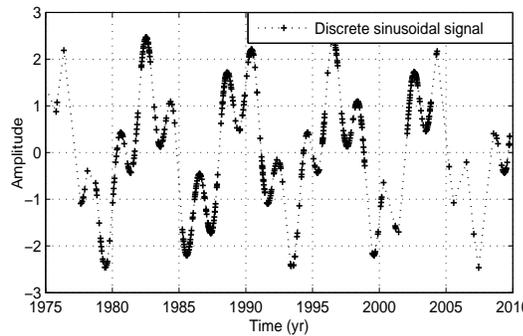
The sample variance within each bin is defined in the same way as

$$s_j^2 = \frac{\sum (x_{kj} - \bar{x}_j)^2}{n_j - 1}, \quad (j = 1, \dots, M),$$

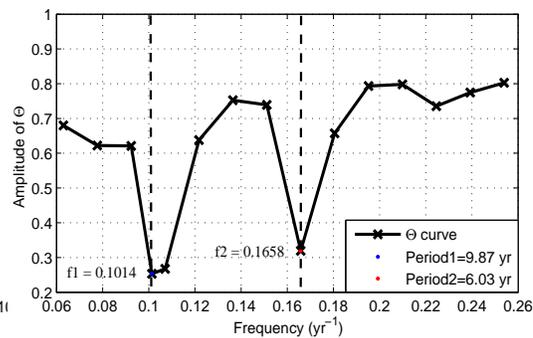
where  $n_j$  is the number of data points in the  $j$ th phase bin. The overall variance for all phase bins  $s^2$  is expressed as

$$s^2 = \frac{\sum (n_j - 1) s_j^2}{\sum n_j - M}, \quad (j = 1, \dots, M). \quad (2)$$

The PDM method picks the mean in each phase bin  $\bar{x}_j$  to construct a mean light curve which is used as a reference of the time variation, then computes the scatter of the data points with respect to the mean light curve. This scatter is quantitatively evaluated by a statistical quantity  $\Theta = s^2/\sigma^2$  (the ratio of the phase bin variance to the total data variance). For a true period,  $\Theta$  will be arbitrarily small; for a false period,  $\Theta$  will be approximately unity. The PDM method searches for a series of testing periods, and finds the periods at which the scatter of the observed light curve from the mean light curve is minimized. A plot of the ratios ( $\Theta$ ) versus trial periods provides an indicator of the best candidates for periodic components. The real periods are identified as the ones corresponding to local minimum values of  $\Theta$  in the plot. The significance of the detected PDM periods has been improved



**Fig. 2** Simulated time series with periods of 10 and 6 yr with different amplitudes. The time span used is the same as that of the observed data for easy comparison.



**Fig. 3** Variation of  $\Theta$  with trial periods. The periods are recognized as the ones at which  $\Theta$  shows a local minimum.

from the original Fisher-Snedecor distribution (Stellingwerf 1978) to a  $\beta$  distribution (Linnell Nemeč & Nemeč 1985; Schwarzenberg-Czerny 1989, 1997). Quantitative evaluation of the significance can be obtained using Monte Carlo simulations.

### 3.2 Testing the PDM Method Using a Simulated Multiple-Period Signal

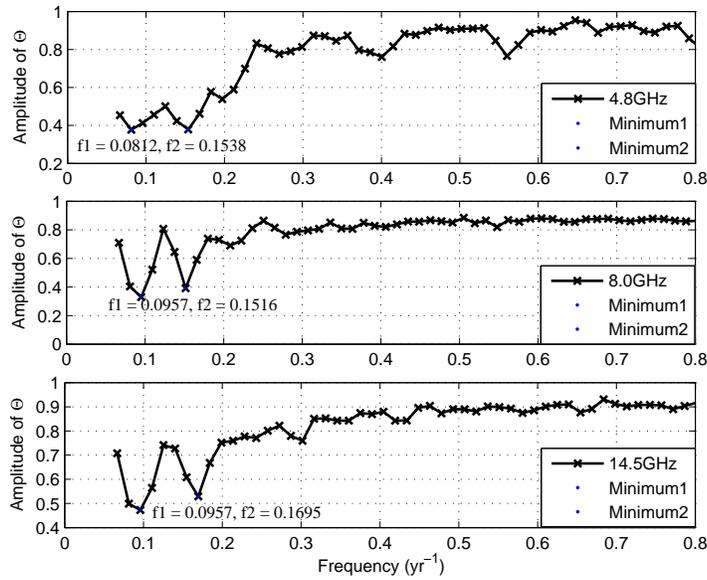
In order to verify the reliability and applicability of the PDM approach, we adopt a simulated time series with a function of  $y = \sin(\frac{\pi}{5}t) + 1.5 \sin(\frac{2\pi}{3}t)$  to perform the PDM analysis. It is a combination of two sinusoidal functions with different periods (10 and 6 yr) and different amplitudes (1.0 and 1.5). This simulated signal is sampled in accordance with the same time interval as observed NRAO 530 data to construct discrete time series. A discrete random noise signal with an amplitude range of [0,0.1] is also added to the time series. The time coverage of the simulated time series is from 1975 to 2010, the same as the observed data.

The simulated signal is shown in Figure 2. The variation of the resulting  $\Theta$  values as a function of trial periods is shown in Figure 3. The plot highlights the two major periods between 0–0.25 ( $\text{yr}^{-1}$ ), and the  $\Theta$  fluctuates between 0.7–0.9 in the higher frequency (shorter period) part of the plot, which is not shown. The plot clearly displays two periods of 9.87 and 6.03 yr, corresponding to the first and secondary minima of  $\Theta$ , respectively. The results agree with the initial definition of 10 and 6 yr periods in the signal function. It demonstrates that PDM is not only able to identify periodic fluctuations, but also to detect multiple periodic components.

### 3.3 PDM Periodogram of NRAO 530

We conducted the PDM analysis in two steps. Firstly, the data were divided into a number of segmentations in a ‘rough-cut’ way. The algorithm performed a broad search for periodic signals with the data gaps removed. This resulted in a group of candidates for the periodic frequencies. Secondly, the segmented data were computed by using the PDM algorithm to scan the trial frequencies near the candidates obtained in the first step. The gaps among the observed data were included in the calculation to obtain more accurate periods. This second scan (‘fine scan’) gives a fine resolution of the detected characteristic frequencies. Running the algorithm in two steps greatly saves computing time, and increases efficiency.

The periodicity search using the PDM method was made across a time baseline of three decades. Considering that the total time span of the monitoring data is about 30–35 yr, it is expected to detect

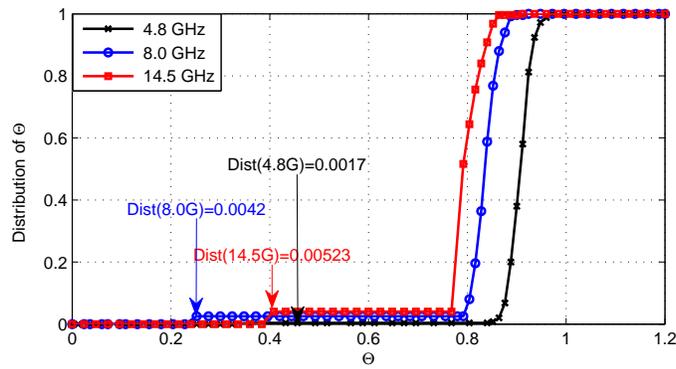


**Fig. 4**  $\Theta$ -frequency diagrams of NRAO 530: 4.8 GHz (*top*), 8.0 GHz (*middle*) and 14.5 GHz (*bottom*). The oscillations are aliases caused by the data gaps.

periodic signals with a few complete cycles during the observed time. Since the PDM approach used in this paper aims at identifying long-period variabilities, we set the trial frequencies to be in the range from 0.067 to 1 ( $\text{yr}^{-1}$ ), which is equivalent to a trial period range of 1–15 yr. Following the procedure of the PDM approach described above with the selected parameters, we obtained the  $\Theta$ -frequency relation at three observing bands.

Figure 4 shows the  $\Theta$  statistics versus the testing frequency for the radio data of NRAO 530. At all three frequencies, the primary and secondary minima are detected at similar positions, i.e.  $\sim 0.0960$  ( $\text{yr}^{-1}$ ) and  $\sim 0.1695$  ( $\text{yr}^{-1}$ ), which correspond to the periodicity time scales of 10.4 and 5.9 yr, respectively. These two minima are less prominent at 4.8 GHz (top panel: Fig. 4) when compared with those at 8.0 GHz (middle panel: Fig. 4) and 14.5 GHz (bottom panel: Fig. 4). The reason might be associated with the increasing opacity at lower observing frequency that tends to smooth the variabilities. In addition to these two significant minima, the diagrams also show some other local less distinct minima. At 14.5 GHz, a minimum  $\Theta_{\min} \sim 0.75$  corresponds to a period of  $\sim 3.2$  yr (frequency =  $0.31 \text{ yr}^{-1}$ ). At 8.0 GHz, a local minimum  $\Theta_{\min} \sim 0.70$  corresponds to a period of  $\sim 4.9$  yr, which is also seen at 4.8 GHz at a similar period of  $\sim 5$  yr. At 4.8 GHz, there are some hints of shorter periods at  $\sim 2.5$  yr and  $\sim 1.8$  yr.

In order to test the statistical significance of the derived periodicities, we performed Monte Carlo simulations (Linnell Nemec & Nemec 1985) of the most prominent periods of  $\sim 6$  and  $\sim 10$  yr. When employing the numerical simulations, the original observed data (the epochs and amplitudes) were used, but the data sequences were randomized. A normal PDM analysis was made again for these randomized data sets using the same parameters adopted for the actual data analysis. The integral of this distribution of  $\Theta_{\min}$  represents an estimate of the probability of the  $\Theta_{\min}$  distribution that could be due to pure noise. The Monte Carlo simulation was repeated 500 times until the full distribution of the noise-generated  $\Theta_{\min}$  distribution was obtained. This distribution was then used to estimate the statistical significance of the testing periods.



**Fig. 5** Statistical significance test using Monte Carlo simulations. Three curves represent the  $\Theta_{\min}$  distribution of the 10-yr periodicity at three radio frequencies of 14.5, 8.0 and 4.8 GHz. The arrows represent the confidence levels of  $\Theta_{\min}$  corresponding to each curve.

**Table 1** Periodicity Analysis Results of NRAO 530 and Monte Carlo Simulations

$\nu$ (GHz)	No.	Freq. ( $\text{yr}^{-1}$ )	$P$ (yr)	$\Theta_{\min}$	Signif Monte Carlo
14.5	1	0.0960	10.4	0.4730	0.00523
	2	0.1695	5.9	0.5293	0.00479
8.0	1	0.0949	10.5	0.3289	0.0042
	2	0.1515	6.6	0.3915	0.0054
4.8	1	0.0812	11.3	0.3778	0.00017
	2	0.1537	6.5	0.3786	0.00035

Figure 5 shows an example of the Monte-Carlo simulation results of 10-yr periodicity after 500 trials. The probabilities for generating a 10-yr period from a pure noise signal for the given frequencies are 0.00523 (14.5 GHz), 0.0042 (8.0 GHz) and 0.0017 (4.8 GHz), which convert to probabilities for a genuine 10-yr period of 99.48% (14.5 GHz), 99.58% (8.0 GHz) and 99.83% (4.8 GHz) respectively. The characteristic periods computed by using the PDM method and the statistical significance derived from the Monte Carlo simulations are tabulated in Table 1. Note that only the two self-consistent periods which appear at all three observing bands are listed. The confidence values of the 6-yr period are 99.52%, 99.46% and 99.97% for 14.5, 8.0 and 4.8 GHz, respectively.

#### 4 COMPARISON WITH RESULTS FROM OTHER METHODS

In order to verify the results derived from the PDM method, we also analyzed the variability data of NRAO 530 making use of the Fourier-transform method (Lomb-Scargle periodgram: Lomb 1976; Scargle 1982, 1989) and wavelet transform method (Grossmann et al. 1989; Foster 1996). The results obtained from the Lomb-Scargle and wavelet methods are discussed in a parallel paper (T. An et al. 2012, in prep.).

The Lomb-Scargle algorithm (LS) is a variation of the discrete Fourier transform (DFT), in which a time series is decomposed into a linear combination of sinusoidal functions. The basis of the algorithm is to transform the data with sinusoidal functions from the time domain to the frequency domain. Scargle (1981, 1982) has developed a set of formulae for the transformation coefficients that have similar forms with the DFTs when computing evenly spaced time series. In addition, an adjustment in calculation of the transformation coefficients has been made to make the transform

**Table 2** Periodicity Analysis of the Radio Light Curves of NRAO 530 with the PDM, LS and WWZ

Method	PDM			LS			WWZ		
$\nu$ (GHz)	4.8	8.0	14.5	4.8	8.0	14.5	4.8	8.0	14.5
Period 1 (yr)	11.3	10.5	10.4	9.5	10.4	9.9	9.7	10.1	9.8
Period 2 (yr)	6.5	6.6	5.9	6.3	6.3	6.2	6.0	6.0	5.9

insensitive to time shifts. The power of the LS periodogram is defined as the inverse of the variance of the fit as a function of the trial frequency. The best-fitted period is identified as the one giving the maximum power. The LS periodogram detected a number of local maxima in the power-period plot, among which the highest two peaks correspond to 6.2- and 10-yr periods (T. An et al. 2012, in prep.). Other lower power peaks indicated shorter-timescale periods of  $\sim 5$ ,  $\sim 4$  and  $\sim 3$  yr.

The wavelet transform is another widely used method for time variability analysis. The peculiar character of the wavelet method is the localization property in both time and frequency domains. This localization property allows the wavelet functions to have limited durations, thus enabling the wavelet transform to capture transient flares or short-lived periodic signals. The basic procedure of wavelet transform analysis is first to construct a mother wavelet, then to convolve the mother wavelet with a set of trial functions. The wavelet functions, in principle, might be of any shape, therefore the wavelet transform may naturally identify the non-sinusoidal periodic signals. T. An et al. (2012, in prep.) used the weighted wavelet  $Z$ -transform (WWZ: Foster 1996) to search for the periodicity of NRAO 530. The powers of the wavelet transform, WWZ, are computed as a function of time ( $t$ ) and oscillation frequency ( $\omega$ ). Two persistent periodicities of  $\sim 6$ -yr and  $\sim 10$ -yr were detected from the WWZ. This is consistent with the results from the present PDM analysis. In addition, some other periodic signals with timescales of  $\sim 5$ ,  $\sim 4$ ,  $\sim 3$  and  $\sim 1.8$  yr were detected but with relatively lower powers. These shorter-timescale periodicities are also detected in the PDM diagrams (Fig. 4). Table 2 compares the major periods detected from the NRAO 530 data using the PDM (the present paper), LS and WWZ methods (T. An et al. 2012, in prep.).

## 5 SUMMARY AND CONCLUSIONS

The PDM method was employed to search for the periodicity from the radio data of NRAO 530. The main results of the present paper can be summarized as:

- (1) Multiple periods of different timescales have been identified. The  $\Theta$ -period diagrams display two distinctive minima that have comparable magnitudes. The corresponding periods are  $\sim 10.5$  yr and  $\sim 6.5$  yr. The self-consistency of these two major periodic signals at all three observing frequencies suggests that the periodic fluctuations of the radio luminosity are associated with persistent dynamic processes. Other periodicities with shorter timescales and less distinction have also been detected.
- (2) The statistical significance of two prominent periods (10- and 6-yr) has been tested using the Monte Carlo technique. The numerical simulations showed high confidences for both periodic signals at all three observing bands, confirming the reality of the PDM results.
- (3) Excellent consistency was demonstrated from the comparison of the periodicity results derived from the PDM, LS and WWZ methods, proving the validity of these numerical techniques in the AGN variability studies.

Different methods arrive at a consistent conclusion that there are multiple periodicities in the radio light curves of NRAO 530. Moreover, the periodicities are found to have a harmonic frequency relation,  $n \times f_1$ , where  $n = 1, 2, 3, \dots$  (T. An et al. 2012, in prep.). However, the fundamental oscillation frequency  $f_1 \approx \frac{1}{20} \text{ yr}^{-1}$  is not detected over the total 35-yr time span. We argue that the two

prominent periods ( $\sim 10$  yr and  $\sim 6$  yr) may represent the 2nd and 3rd harmonics. The higher-order harmonics are suppressed during the active periods of radio outbursts. The multiple harmonics of the periods seem to not be a unique property of NRAO 530. This phenomenon has also been observed in other blazars, such as 3C 279 (Liu et al. 2006) and 1510–089 (Xie et al. 2008). Physical processes related to precessing jets driven by orbiting black hole binaries or warped accretion disks are not satisfactory to explain the present observations. However,  $p$ -mode oscillations triggered by disk instabilities can provide reasonable interpretations of the multiple periodicities and their harmonic relations (T. An et al. 2012, in prep.). Variability studies of a large sample of blazars are necessary to verify whether the results of the present analysis and their implications are universal.

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