OPTICAL MONITORING OF 3C 390.3 FROM 1995 TO 2004 AND POSSIBLE PERIODICITIES IN THE HISTORICAL LIGHT CURVE

JUN TAO1,2, JUNHUI FAN1,3, BOCHEN QIAN1,2, and YI LIU3

1 Shanghai Astronomical Observatory, CAS, 80 Nandan Road, Shanghai, 200030, China; taojun@shao.ac.cn
2 Joint Institute for Galaxies and Cosmology, SHAO and USTC, CAS, Shanghai, China
3 Center for Astrophysics, Guangzhou University, Guangzhou 510006, China
4 Physics Institute, Hunan Normal University, Changsha, China

Received 2007 July 27; accepted 2007 November 23; published 2008 January 17

Abstract

We report V, R, and I band CCD photometry of the radio galaxy 3C 390.3 obtained with the 1.56 m telescope of the Shanghai Astronomical Observatory from 1995 March to 2004 August. Combining these data with data from the literature, we have constructed a historical light curve from 1894 to 2004 and searched for periodicities using the CLEANest program. We find possible periods of 8.30 ± 1.17, 5.37 ± 0.49, 3.51 ± 0.21, and 2.13 ± 0.08 yr.

Key words: galaxies: active – galaxies: individual (3C 390.3) – galaxies: photometry – galaxies: Seyfert – methods: data analysis

Online-only material: color figures

1. INTRODUCTION

Active galactic nuclei (AGNs) can be divided into two classes: radio-loud and radio-quiet. A small subgroup of radio-loud AGNs have displayed flux variability on time scales ranging from hours to decades (see a review by Fan 2005). Examples of long-term variations can be found in the light curves of 3C 120 (Jurkevich et al. 1971), OJ 287 (Sillanpää et al. 1988), 3C 345 (Kiger et al. 1992), PKS 0735+178 (Pollock 1975; Fan et al. 1997; Qian & Tao 2004), BL Lacertae (Fan et al. 1998), 3C 66A (Lainela et al. 1999), 3C 279 (Fan 1999), S5 0716+714 (Fan et al. 2002), 3C 390.3 (Prieto 1997). It is also a highly variable radio-loud and radio-quiet. A small subgroup of radio-loud AGNs have displayed flux variability on time scales ranging from hours to decades (see a review by Fan 2005). Examples of long-term variations can be found in the light curves of 3C 120 (Jurkevich et al. 1971), OJ 287 (Sillanpää et al. 1988), 3C 345 (Kiger et al. 1992), PKS 0735+178 (Pollock 1975; Fan et al. 1997; Qian & Tao 2004), BL Lacertae (Fan et al. 1998), 3C 66A (Lainela et al. 1999), 3C 279 (Fan 1999), S5 0716+714 (Fan et al. 2002), Mrk 335 (Tao et al. 2004), PKS 1510−089 & MA 0829+047 (Liller & Liller 1975), B2 1101+38 (Miller 1975) and in various other radio-selected BL Lacertae objects (Fan et al. 2002).

3C 390.3 (z = 0.0561; Osterbrock et al. 1975) is a well-known broad-line radio galaxy with a broad double-peaked emission-line profile (Sandage 1966; Lynds 1968). It is also an extended double-lobed FR II radio source. Leahy & Perley (1995) discussed the jets and hotspots of it, and they also provided some basic data of this source. The very long baseline interferometry (VLBI) observations at 5 GHz show evidence of superluminal motions, with v/c ≈ 4.0 (Alef et al. 1996).

3C 390.3 has a well-known history, both in the continuum light and in emission lines (e.g., Dietrich et al. 1998; Shapovalova et al. 2001; Sandage 1967, 1973; Zheng 1996). Prieto & Kotilainen (1997) detected optically resolved emission coincident with the brightest region of the northern radio lobe (hotspot B) in the B, R, and I bands. Dunn et al. (2006) provided a data base of ultraviolet continuum light curves for AGNs, and 3C 390.3 is one of them. ROSAT PSPC of 3C 390.3 shows resolved X-ray emission spatially located at the position of the northern radio hotspot (Prieto 1997). It is also a highly variable X-ray source (Inda et al. 1994; Eracleous et al. 1996; Wozniak et al. 1998; Leighly et al. 1997; Leighly & O’Brien 1997; Gliozzi et al. 2003). Gaskell (2006) discussed the relationship between the X-ray, UV, and optical variability in 3C 390.3. The narrow-line region (NLR) in 3C 390.3 is probably of the order of 1 lt-yr, and a significant part of the NLR is located near the line of sight (Zheng et al. 1995). The black hole mass of 3C 390.3 has been estimated through reverberation mapping (e.g., McLure & Dunlop 2001; Botte et al. 2004; Shapovalova et al. 2001), ranging from 2.2 × 10⁸ to 2.1 × 10⁹ M☉.

3C 390.3 has been one of our primary targets for long-term monitoring in the optical band at the Shanghai Astronomical Observatory (SHAO). In this paper, we present V, R, and I data taken in the period from 1995 to 2004. We also compile historical data from 1894 to 2004. We obtain a total of 786 observational points, to which we adopt the CLEANest method to search for periodicities.

2. OBSERVATIONS AND DATA REDUCTION

The observations presented here were obtained with the 1.56 m telescope at SHAO from 1995 March 6 to 2004 August 14. At first a liquid-nitrogen-cooled CCD camera (1024 × 1024 pixels, 1 pixel = 0.019 mm) was used. The field of view of this was 4.3 arcmin (1 pixel = 0.25 arcsec) when used directly at the Cassegrain focus, and approximately 13 arcmin (1 pixel = 0.76 arcsec) when used with a focal reducer. A new liquid-nitrogen-cooled CCD camera (2048 × 2048 pixels, SITe CCD chip) has been used since 2002 August. The chip of this camera subtends 11 arcmin by 11 arcmin in sky, with a scale of 0.31 arcsec per pixel (1 pixel = 0.024 mm). Standard Johnson–Cousins V, R, and I filters were used. Typical integration times were 300 s for I and R, and 600 s for filter V, depending on sky conditions and the brightness of 3C 390.3. The flat-field images were taken at dusk and dawn. The bias images were taken at the beginning and the end of the observations, while the dark-field images were taken at the end. All observing data were processed using the IRAF software package.

The seeing at the Sheshan Station of SHAO varied from 1.3 to 2.0 arcsec full width at half-maximum (FWHM), and we have discussed this elsewhere (see Figure 3 of Qian et al. 2002). Since 3C 390.3 is not a point-like source, seeing fluctuations may have an effect. Thus, we have followed the recommendations of Cellone et al. (2000) and selected a photometric aperture of radius 6.5 arcsec to minimize potential seeing-dependent effects. Cellone et al. (2000) gave the minimum aperture radii to which we adopt the CLEANest method to search for periodicities.

The seeing at the Sheshan Station of SHAO varied from 1.3 to 2.0 arcsec full width at half-maximum (FWHM), and we have discussed this elsewhere (see Figure 3 of Qian et al. 2002). Since 3C 390.3 is not a point-like source, seeing fluctuations may have an effect. Thus, we have followed the recommendations of Cellone et al. (2000) and selected a photometric aperture of radius 6.5 arcsec to minimize potential seeing-dependent effects. Cellone et al. (2000) gave the minimum aperture radii to which we adopt the CLEANest method to search for periodicities.
a 5 arcsec radius aperture, which is also comparable to the one we have used. We used comparison stars A, B, and D of Penston et al. (1971) and Hubble Space Telescope (HST) GS 4951:731. \(V\), \(R\), and \(I\) magnitudes were taken from Dietrich et al. (1998). Using differential photometry with respect to each comparison star, \(c_i, i = 1 - n\), within the frame we obtain a magnitude \(m_i\) for the object of interest. Then, the object’s magnitude at that time is

\[
\bar{m} = \frac{\sum m_i}{n},
\]

where \(n\) is the number of standard stars, in this case, four. The uncertainty \(\sigma_1\) was calculated as

\[
\sigma_1 = \sqrt{\frac{\sum (m_i - \bar{m})^2}{n - 1}}.
\]

The difference between comparison stars is

\[
\sigma_2 = (m_A - m_B) - \Delta m_{AB},
\]

where \(\Delta m_{AB}\) is the magnitude difference of comparison stars A and B as given by Dietrich et al. (1998), and \(m_A\) and \(m_B\) are the observed magnitudes of comparison stars A and B. The absolute value of \(\sigma_2\) was used as an additional indicator of the observational uncertainty.

The observational data are listed in Tables 1–3, in which the first column gives the Julian date, the second the magnitudes, the third the \(\sigma_1\) uncertainties, and the fourth the \(\sigma_2\) uncertainties.

### 3. THE LIGHT CURVES

Figures 1–3 show the light curves of 3C 390.3 and the magnitude differences between comparison stars A and B in the \(V\), \(R\), and \(I\) filters, respectively. In our observation period from 1995 March to 2004 August, variations of \(1^m\) 372 (15.023 to 16.395) in the \(V\) band, \(1^m\) 240 (14.352 to 15.592) in the \(R\) band, and \(1^m\) 284 (13.896 to 15.180) in the \(I\) band are found. The observations show that 3C 390.3 was brightening from 1995 and reached its brightest in 1996 September. Then it slowly declined in brightness, but was brightening again in 2003 September.

We have compared our results with those of Dietrich et al. (1998). Our data have 10 days of overlap with the data of Dietrich et al. We converted their published flux data of 3C 390.3 to \(V\) magnitudes by taking \(V = -2.5 \times \log(f) + 17.961\). For each day, the observational data were averaged and they are shown in Figure 4. This comparison gave the relationship used to convert their fluxes to \(V\) magnitudes.
Table 2
R-band Magnitudes of 3C 390.3

| Date (ID 2,449,000+) | Magnitude | $\sigma_1$ | $\sigma_2$ |
|----------------------|-----------|------------|------------|
| 802.2093             | 15.206    | 0.052      | 0.073      |
| 802.3039             | 15.322    | 0.038      | -0.025     |
| 803.3159             | 15.270    | 0.018      | -0.003     |
| 819.0507             | 15.265    | 0.015      | 0.034      |
| 824.1183             | 15.234    | 0.040      | 0.049      |
| 845.1945             | 15.111    | 0.014      | 0.019      |
| 919.0410             | 15.305    | 0.028      | 0.052      |
| 924.0838             | 15.288    | 0.022      | 0.027      |
| 935.0480             | 15.149    | 0.015      | 0.027      |
| 943.0366             | 15.099    | 0.014      | -0.005     |
| 943.0098             | 15.098    | 0.014      | -0.004     |
| 947.0513             | 15.191    | 0.037      | 0.032      |
| 947.0587             | 15.154    | 0.035      | 0.066      |
| 977.9743             | 15.027    | 0.003      | -0.004     |
| 977.9790             | 15.033    | 0.007      | -0.010     |
| 977.9834             | 15.023    | 0.020      | 0.013      |
| 1196.2565            | 14.660    | 0.021      | 0.021      |
| 1196.2876            | 14.608    | 0.040      | 0.021      |
| 1197.2695            | 14.698    | 0.019      | 0.003      |
| 1197.2740            | 14.661    | 0.024      | -0.029     |
| 1199.2660            | 14.820    | 0.035      | 0.041      |
| 1199.2722            | 14.775    | 0.044      | 0.056      |
| 1221.0993            | 14.769    | 0.024      | 0.035      |
| 1257.0738            | 14.880    | 0.054      | 0.034      |
| 1257.0799            | 14.871    | 0.045      | -0.052     |
| 1328.0826            | 14.352    | 0.019      | 0.028      |
| 1328.0873            | 14.402    | 0.082      | 0.048      |
| 1328.0929            | 14.504    | 0.060      | 0.003      |
| 1332.0358            | 14.944    | 0.067      | -0.095     |
| 1371.9859            | 14.656    | 0.062      | 0.030      |
| 1371.9889            | 14.718    | 0.086      | 0.031      |
| 1550.3524            | 15.144    | 0.012      | -0.027     |
| 1550.3569            | 15.083    | 0.020      | 0.028      |
| 1577.3114            | 15.083    | 0.045      | 0.056      |
| 1577.3167            | 15.029    | 0.039      | 0.061      |
| 1577.3217            | 15.078    | 0.034      | 0.052      |
| 1577.3267            | 14.978    | 0.040      | 0.059      |
| 1577.3330            | 14.990    | 0.039      | 0.062      |
| 1586.2576            | 14.828    | 0.046      | 0.069      |
| 1586.2617            | 15.274    | 0.032      | 0.038      |
| 1586.2704            | 15.169    | 0.020      | 0.007      |
| 1586.2747            | 15.171    | 0.023      | 0.022      |
| 1586.2793            | 15.213    | 0.042      | 0.069      |
| 1594.2340            | 15.122    | 0.042      | 0.065      |
| 1594.2422            | 14.994    | 0.024      | -0.012     |
| 1594.2447            | 15.196    | 0.024      | 0.019      |
| 1599.1528            | 15.192    | 0.047      | 0.060      |
| 1614.2360            | 15.219    | 0.015      | 0.019      |
| 1614.2418            | 15.191    | 0.016      | 0.016      |
| 1616.1541            | 15.138    | 0.020      | 0.029      |
| 1616.1572            | 15.211    | 0.015      | 0.021      |
| 1616.1600            | 15.271    | 0.030      | 0.056      |
| 1660.1492            | 15.339    | 0.034      | 0.008      |
| 1660.1524            | 15.210    | 0.021      | 0.012      |
| 1691.9937            | 15.205    | 0.014      | -0.015     |
| 1691.9959            | 15.198    | 0.012      | 0.020      |
| 1691.9981            | 15.217    | 0.018      | -0.005     |
| 1692.0182            | 15.181    | 0.014      | 0.027      |
| 1692.0209            | 15.170    | 0.027      | 0.032      |
| 1692.0234            | 15.223    | 0.030      | 0.005      |
| 1699.1292            | 15.067    | 0.029      | 0.009      |
| 1699.1339            | 15.181    | 0.034      | 0.045      |
| 1701.0020            | 15.317    | 0.029      | 0.024      |
| 1701.0053            | 15.301    | 0.007      | 0.013      |
| 1701.0087            | 15.373    | 0.006      | 0.003      |
| 1701.0122            | 15.380    | 0.029      | -0.042     |

Figure 1. V-band light curve of 3C 390.3 (top) with the relative difference between comparison stars A and B (bottom).

Dunn et al. (2006) determined the UV light curves of 3C 390.3 using the Multimission Archive at the Space Telescope Science Institute (STScI). The data were observed with the International Ultraviolet Explorer, from 1978 to 1996. The light curves of the three bands, centered at 1431, 1816, and 1912 Å, all show
### Table 3

| Date (JD 2,449,000+) | Magnitude | $\sigma_1$ | $\sigma_2$ |
|----------------------|-----------|------------|------------|
| 783.3399             | 14.635    | 0.019      | −0.036     |
| 783.3429             | 14.627    | 0.028      | −0.008     |
| 783.3463             | 14.719    | 0.021      | −0.038     |
| 783.3556             | 14.696    | 0.022      | −0.044     |
| 802.3145             | 14.470    | 0.014      | −0.002     |
| 803.3013             | 14.600    | 0.019      | −0.029     |
| 803.3078             | 14.551    | 0.019      | −0.023     |
| 845.2020             | 14.332    | 0.023      | −0.004     |
| 845.2187             | 14.575    | 0.028      | 0.017      |
| 845.2234             | 14.566    | 0.030      | 0.030      |
| 919.0351             | 14.645    | 0.041      | 0.023      |
| 919.0451             | 14.629    | 0.038      | −0.031     |
| 924.0796             | 14.630    | 0.045      | −0.025     |
| 924.1049             | 14.690    | 0.056      | 0.020      |
| 934.0925             | 14.567    | 0.028      | −0.043     |
| 935.0950             | 14.505    | 0.040      | −0.076     |
| 935.0935             | 14.491    | 0.041      | −0.036     |
| 942.9644             | 14.568    | 0.022      | −0.018     |
| 942.9920             | 14.536    | 0.035      | −0.017     |
| 947.0385             | 14.547    | 0.065      | −0.001     |
| 947.0445             | 14.623    | 0.066      | −0.001     |
| 961.0682             | 14.409    | 0.035      | −0.017     |
| 961.9741             | 14.452    | 0.054      | −0.032     |
| 961.9825             | 14.431    | 0.037      | −0.012     |
| 977.9529             | 14.374    | 0.041      | 0.003      |
| 977.9578             | 14.432    | 0.039      | −0.032     |
| 977.9626             | 14.389    | 0.092      | −0.184     |
| 1196.2602            | 14.105    | 0.023      | −0.013     |
| 1196.2785            | 14.096    | 0.039      | −0.092     |
| 1197.2588            | 14.081    | 0.033      | 0.036      |
| 1197.2646            | 14.223    | 0.032      | 0.044      |
| 1199.2347            | 14.287    | 0.016      | −0.004     |
| 1199.2490            | 14.219    | 0.025      | 0.000      |
| 1199.2556            | 14.220    | 0.022      | −0.026     |
| 1221.0931            | 14.098    | 0.028      | 0.034      |
| 1257.0579            | 14.292    | 0.019      | −0.007     |
| 1257.0645            | 14.238    | 0.031      | 0.004      |
| 1371.9801            | 14.117    | 0.028      | −0.042     |
| 1550.3434            | 14.394    | 0.018      | 0.026      |
| 1550.3469            | 14.346    | 0.037      | 0.053      |
| 1577.2501            | 14.452    | 0.009      | 0.004      |
| 1577.2542            | 14.439    | 0.022      | 0.026      |
| 1577.2606            | 14.537    | 0.024      | 0.004      |
| 1577.2678            | 14.491    | 0.024      | −0.012     |
| 1577.2715            | 14.469    | 0.020      | 0.013      |
| 1578.2352            | 14.378    | 0.040      | 0.035      |
| 1578.2389            | 14.553    | 0.065      | 0.096      |
| 1578.2842            | 14.512    | 0.047      | 0.019      |
| 1578.2877            | 14.503    | 0.069      | 0.075      |
| 1586.3170            | 14.578    | 0.014      | −0.021     |
| 1586.3204            | 14.586    | 0.025      | 0.016      |
| 1586.3255            | 14.575    | 0.027      | 0.035      |
| 1594.2498            | 14.530    | 0.030      | 0.041      |
| 1594.2519            | 14.508    | 0.021      | 0.011      |
| 1594.2536            | 14.519    | 0.036      | 0.040      |
| 1599.1410            | 14.556    | 0.040      | 0.039      |
| 1599.1462            | 14.559    | 0.030      | 0.048      |
| 1614.1925            | 14.625    | 0.040      | −0.085     |
| 1614.1991            | 14.602    | 0.031      | −0.065     |
| 1614.2020            | 14.578    | 0.032      | −0.062     |
| 1616.1458            | 14.620    | 0.013      | 0.011      |
| 1616.1483            | 14.536    | 0.092      | 0.015      |
| 1616.1509            | 14.528    | 0.091      | 0.033      |
| 1660.1375            | 14.905    | 0.041      | −0.027     |
| 1660.1424            | 14.353    | 0.060      | 0.011      |
| 1660.1455            | 14.488    | 0.027      | −0.013     |

(Continued)
Table 3 (Continued)

| Date (JD 2,449,000+) | Magnitude | $\sigma_1$ | $\sigma_2$ |
|----------------------|-----------|------------|------------|
| 3124.1323            | 14.510    | 0.039      | -0.042     |
| 3760.2646            | 14.261    | 0.013      | 0.025      |
| 3760.2955            | 14.570    | 0.042      | 0.060      |
| 3795.2334            | 13.896    | 0.047      | -0.067     |
| 3795.2569            | 13.978    | 0.074      | -0.104     |
| 3855.1142            | 14.204    | 0.008      | 0.012      |
| 3855.1228            | 14.499    | 0.068      | 0.097      |
| 3856.0373            | 14.286    | 0.188      | -0.267     |
| 3856.0435            | 14.180    | 0.060      | -0.085     |
| 3857.9957            | 14.200    | 0.066      | 0.094      |
| 3886.0060            | 14.187    | 0.127      | -0.180     |
| 3886.0105            | 14.106    | 0.016      | -0.022     |
| 3886.0435            | 14.180    | 0.060      | -0.085     |
| 3887.9957            | 13.987    | 0.078      | 0.110      |
| 3888.0066            | 15.106    | 0.021      | 0.030      |
| 3888.0216            | 15.180    | 0.042      | -0.059     |

Figure 2. $R$-band light curve of 3C 390.3 (top) with the relative differences between comparison stars A and B (bottom).

Figure 3. $I$-band light curve of 3C 390.3 (top) with the relative differences between comparison stars A and B (bottom).

Figure 4. Comparison of the flux data given by Dietrich et al. (1998) with our $V$-band data. The Dietrich et al. fluxes have been converted to magnitudes using the relationship $V = -2.5 \times \log(f) + 17.961$.

Figure 5. Comparison of $B$ and $V$ magnitudes given by Shapovalova et al. (2001).

a brightening trend from JD 2,449,750 to JD 2,450,162, which is consistent with our $V$, $R$, and $I$ light curves for the same period.

4. THE HISTORICAL LIGHT CURVE AND POSSIBLE PERIODICITIES

4.1. Historical Light Curve

We have reconstructed the historical light curve by combining our recent data with data from the literature (Cannon et al. 1971; Selmes et al. 1975; Dietrich et al. 1998; Scott et al. 1976; Sergeev et al. 2002; Lloyd 1984; Shapovalova et al. 2001; Sandage 1967, 1973; Shen et al. 1972; Yee & Oke 1981; Pica et al. 1980, 1988). Most of these data sets are for the $V$ band or a continuum near the $V$ band. However, there are some $B$-band data in the remaining papers. In order to include these data, we needed to convert them to $V$-band magnitude. Shapovalova et al. (2001) provide simultaneous $B$ and $V$ data (see Figure 5). From their data we find that $V = 7.234 + 0.508B$ with a standard deviation of...
0.052 mag. This relationship was then used to convert B-band magnitudes to V-band magnitudes to give a historical light curve in the V band. This has a total of 786 observational points over a time interval of 111 yr (from 1894 to 2004). We show the historical light curve in Figure 6. It shows two outbursts (1970 and 1996) and a possible third (near 1939).

4.2. Periodicity Analysis

Using the historical light curve we have constructed for 3C 390.3, we searched for possible periodicities.

As in our previous papers (Fan et al. 2006, 2007), we use the CLEANest analysis (Foster 1995) to search for periodicities. The CLEANest analysis cleans spurious periodicities as follows. First, the strongest single peak and corresponding aliases are subtracted from the original spectrum, then the residual spectrum is scanned to determine whether the next-strongest remaining peak is statistically significant. If so, then the original data are analyzed to find the pair of frequencies which best model the data, these two peaks and corresponding aliases are subtracted, and the residual spectrum is scanned again. The process continues, producing successive CLEANest spectra, until all statistically significant frequencies are included.

The light curve of 3C 390.3 shows that the data are unevenly sampled with most data concentrated in the period from 1965 to 2004. Observations before 1933 are particularly sparse. After using the CLEANest algorithm on the 1933–2004 data set we find that there are seven independent frequency components required to “clean” the light curve. The CLEANest spectrum is shown in Figure 7. For comparison, in Figure 8 we show the results of using only the post-1965 data.

When analyzing unevenly sampled time series, the irregular spacing introduces many complications into the Fourier transformations; it can alter peak frequencies (slightly) and amplitudes (greatly), and even introduce extremely large spurious peaks. Including all 3C 390.3 data points would not only give irregular sampling but also give undue weight to the most recent 40 yr of data. To obtain regular sampling and to give more uniform weighting to different epochs we binned the data from 1933 onwards. However, binning data inevitably throws away information. To minimize this we adopted a bin size of 0.02 yr (7.30 days) which is short enough compared to the long-term periods we are looking for (years) and thus unlikely to distort long-term variations. This binning gives us 361 points in the binned light curve from 1933 to 2004. In Figure 9 we show the CLEANest spectrum for this binned light curve.

We also investigated the effect of removing a long-term linear trend in the binned 1933–2004 historical light curve using \( V(\text{magnitude}) = -0.849005 + 0.00820992 \times t(\text{yr}) \). In Figure 10 we show the CLEANest spectrum for this light curve.

Following Foster (1996), the variance of a frequency \( \text{Var}(\omega) \) and the variance of the amplitude of the given frequency \( \text{Var}(P) \)
Figure 8. As for Figure 7 but only for the light curve from 1965 to 2004. One CLEANest frequency component is beyond the range of the figure.

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

Figure 9. As for Figure 7 but for the binned V-band light curve from 1933 to 2004. In the CLEANest spectrum, six CLEANest frequency components (thick vertical lines) and the residual spectrum are shown, one CLEANest component with a frequency of 1.57 yr$^{-1}$, and an amplitude of 0.149 is off the figure.

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

can be estimated by

$$\text{Var}(\omega) = \frac{24\sigma_{\text{res}}^2}{NA^2T^2}$$

$$\text{Var}(P) = \frac{2\sigma_{\text{res}}^2}{N},$$

where $\sigma_{\text{res}}$ is the variance of the residual data, $A$ is the amplitude of the given frequency, $T$ is the total time span, and $N$ means the number of data values in an observed time series. The $\sigma_{\text{res}}^2$ is estimated by

$$\sigma_{\text{res}}^2 = \frac{NV_{\text{res}}}{N - 3f - 1},$$

where $V_{\text{res}}$ is the variance of residual data, $V_{\text{res}} = \langle \text{res} | \text{res} \rangle - \langle 1 \rangle \langle \text{res} \rangle$, and $f$ is the number of discrete frequencies. $|x\rangle$ represents a vector in an $N$-dimensional vector space.

$|x\rangle = [x(t_1), x(t_2), \ldots, x(t_N)].$

Defining the inner product of two vectors, $|f\rangle$ and $|g\rangle$, as the average value of the product $fg$ over the sampling $t_\alpha$

$$\langle f | g \rangle = \frac{\sum_{\alpha=1}^{N} f(t_{\alpha}) g(t_{\alpha})}{N}.$$

Defining the constant vector $|1\rangle$ as

$$|1\rangle = [1, 1, \ldots, 1],$$
the variation of a vector $|f|$ is

$$V_f = \langle f|f \rangle - \langle |f|^2 \rangle.$$

(10)

The results of these four CLEANest analyses are listed in Table 4 and we also give the False Alarm Probability (FAP) of each of the CLEANest frequency components, which depends on the amplitude. Small FAP values support the reality of these periodicities (see Fan et al. 2006 for details).

The unbinned V-band data, the binned data, the linear-trend-removed data, and the post-1965 data (see Table 4) all show that there are apparent periodicities. Those matched periods derived from the first three data sets are 13,298 ± 6298 days (15,268 ± 10,857 days), 3700 ± 413 days (3296 ± 387 days, 3026 ± 427 days), 1871 ± 106 days (1759 ± 110 days, 1961 ± 179 days), 1297 ± 51 days (1282 ± 77 days), and 775 ± 18 days (775 ± 21 days, 776 ± 28 days). However, since the period 13,298 ± 6298 days (15,268 ± 10,857 days) is almost the length of the data coverage, the period is not a physically significant one. From Figure 6, we can see that most data were sampled in the period 1965–2004 (about 40 yr). Therefore, we reinvestigated periods based on the post-1965 data. The matched periods derived from the V-band data (1933–2004) and the post-1965 data (1965–2004) are 7022 ± 1486 days (7203 ± 1564 days), 3700 ± 413 days (3660 ± 404 days), 1297 ± 51 days (1306 ± 51 days), 847 ± 22 days (847 ± 22 days), and 238 ± 2 days (238 ± 2 days). In Table 4, we also present the phase of the corresponding period. Phase and period can be used to identify a signal in multi-data set. We used the obtained components to fit all the light curves, and the results are shown in Figure 11.

According to the data processing theory, the results derived from the linear-trend-removed data set is more reliable. So the possible periods are 8.30 ± 1.17, 5.37 ± 0.49, 3.51 ± 0.21, and 2.13 ± 0.08 yr.

### Table 4

| Period (d) | Amplitude | Phase (rad) | FAP |
|------------|-----------|-------------|-----|
| 7022 ± 1486 | 0.676 ± 0.083 | −0.81 ± 0.12 | 0.002 |
| 3700 ± 413 | 0.325 ± 0.083 | −1.00 ± 0.26 | 0.005 |
| 1871 ± 106 | 0.195 ± 0.083 | 0.92 ± 0.43 | 0.006 |
| 1297 ± 51 | 0.218 ± 0.083 | −0.40 ± 0.38 | 0.006 |
| 847 ± 22 | 0.321 ± 0.083 | −0.13 ± 0.26 | 0.005 |
| 775 ± 18 | 0.315 ± 0.083 | 0.73 ± 0.26 | 0.005 |
| 238 ± 2 | 0.154 ± 0.083 | −0.99 ± 0.54 | 0.007 |

| Period (d) | Amplitude | Phase (rad) | FAP |
|------------|-----------|-------------|-----|
| 13298 ± 6298 | 0.648 ± 0.109 | −0.79 ± 0.17 | 0.003 |
| 8738 ± 2720 | 0.598 ± 0.109 | 0.41 ± 0.18 | 0.003 |
| 3296 ± 387 | 0.187 ± 0.109 | −0.69 ± 0.58 | 0.008 |
| 1759 ± 110 | 0.283 ± 0.109 | −0.70 ± 0.38 | 0.006 |
| 947 ± 32 | 0.240 ± 0.109 | 0.86 ± 0.45 | 0.006 |
| 775 ± 21 | 0.313 ± 0.109 | 0.93 ± 0.40 | 0.005 |
| 233 ± 2 | 0.149 ± 0.109 | 0.21 ± 0.58 | 0.009 |

| Period (d) | Amplitude | Phase (rad) | FAP |
|------------|-----------|-------------|-----|
| 15268 ± 10857 | 0.687 ± 0.109 | −0.52 ± 0.16 | 0.002 |
| 3026 ± 427 | 0.218 ± 0.109 | −0.95 ± 0.50 | 0.007 |
| 1961 ± 179 | 0.224 ± 0.109 | −0.26 ± 0.49 | 0.007 |
| 1282 ± 77 | 0.276 ± 0.109 | −0.11 ± 0.40 | 0.006 |
| 1169 ± 64 | 0.188 ± 0.109 | 0.00 ± 0.58 | 0.007 |
| 776 ± 28 | 0.273 ± 0.109 | −0.11 ± 0.40 | 0.006 |
| 642 ± 19 | 0.207 ± 0.109 | −0.57 ± 0.53 | 0.007 |

| Period (d) | Amplitude | Phase (rad) | FAP |
|------------|-----------|-------------|-----|
| 7203 ± 1564 | 0.758 ± 0.082 | −0.19 ± 0.11 | 0.002 |
| 3660 ± 404 | 0.347 ± 0.082 | −0.59 ± 0.24 | 0.004 |
| 1306 ± 51 | 0.253 ± 0.082 | 0.06 ± 0.33 | 0.005 |
| 928 ± 26 | 0.342 ± 0.082 | −0.91 ± 0.24 | 0.004 |
| 847 ± 22 | 0.332 ± 0.082 | −0.67 ± 0.25 | 0.004 |
| 573 ± 10 | 0.137 ± 0.082 | −0.11 ± 0.61 | 0.008 |
| 238 ± 2 | 0.127 ± 0.082 | −0.61 ± 0.66 | 0.008 |

Figure 10. As for Figure 7 but with a linear trend removed from the light curve (see text). In the CLEANest spectrum, seven CLEANest frequency components are shown by thick vertical lines.

(A color version of this figure is available in the online journal)
5. DISCUSSION AND CONCLUSIONS

AGNs are variable throughout the electromagnetic spectrum. In our monitoring program, we have observed the galaxy 3C 390.3 from 1995 March to 2004 August. The observations clearly show that the source is variable in the optical band with the variation amplitude of $1^{m}372$, $1^{m}240$, and $1^{m}284$ in the V, R, and I bands, respectively. The V band historical light curve is compiled, which has a time span of 111 yr. Possible periods of $8.30 \pm 1.17, 5.37 \pm 0.49, 3.51 \pm 0.21$, and $2.13 \pm 0.08$ yr were found in the light curve by means of the CLEAnest method.

It has been suggested that the long-term periodic outbursts of OJ 287 may be explained by a binary black hole (Sillanpää et al. 1988), or such outbursts may be due to thermal and viscous instabilities in a thin accretion disk (Meyer & Meyer-Hofmeister 1984; Horiuchi & Kato 1990). The historical light curve of 3C 390.3 shows strong variability. Several possible periods were found by the CLEAnest method. The multiple periods we derived may imply the instabilities in the disk. The analysis of spectra of 3C 390.3 covering a period of over 20 yr may indicate the binary black hole model (Gaskell 1996). Shapovalova et al. (2001) have monitored this object between 1995 and 2000. Their results do not support either the models of outflowing biconical gas streams or those of supermassive binary black holes. They conclude that they favor the accretion disk model.

This work is partially supported by the Joint Laboratory for Optical Astronomy of Chinese Academy of Sciences, the National Natural Science Foundation of China (10573005, 10633010), the 973 project (No. 2007CB815405), and Science & Technology Commission of Shanghai Municipality (06DZ22101). We thank Martin Gaskell for editing the English and for comments. We are grateful to the referee, Dr. Paul Viita, for his valuable comments.

REFERENCES

Alef, W., et al. 1996, A&A, 308, 376
Botte, V., et al. 2004, AJ, 127, 3168
Cannon, D. R., et al. 1971, MNRAS, 152, 79
Cellone, S. A., Romero, G. E., & Combi, J. A. 2000, AJ, 119, 1534
Dietrich, M., et al. 1998, ApJS, 115, 185
Dunn, J. P., et al. 2006, PASP, 118, 572
Eracleous, M., et al. 1996, ApJ, 459, 89
