A Search for a Pulsar in the Remnant of SN1987A with the Hubble Space Telescope High Speed Photometer[1]

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Abstract

The High Speed Photometer (HSP) on the Hubble Space Telescope (HST) observed the remnant of SN1987A on four different epochs between 1992 June 2 and 1993 November 4 in a 1600-7000 Å bandpass. Each observation was approximately 40 minutes in duration and used a 100 microsecond sampling time. Assuming a Crab pulsar-like spectrum with similar reddening, the observed count rates imply a time-averaged magnitude $V \approx 18.2$. After correcting to the barycenter of the solar system, no periodic signal was found in any data set using autocorrelation function (ACF) analyses with lags from 200 microseconds to 10 s and power spectral function (PSF) analyses with a Nyquist frequency corresponding to a period of 200 microseconds, or in trial pulse profiles obtained by binning the data modulo the frequencies of highest significance in the ACF and PSF analyses. Searches for signals with large values of $\dot{P}$ also proved

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negative. We estimate an upper limit of V fainter than about 24 for pulsed radiation from any stellar remnant of SN1987A.

Subject headings: pulsars: individual (SN1987A) – techniques: photometric – ultraviolet: stars

1 Introduction

The discovery of a pulsar in the remnant of Supernova 1987A would confirm theoretical predictions (Arnett et al. 1989; Burrows 1989) about this important phase of the stellar life cycle. It would also be the first pulsar with a previously observed progenitor star. Several groups have attempted to detect pulsed radiation at different wavelengths, resulting in the reported detection of a sub-millisecond signal in the visible that was later retracted (Kristian et al. 1989; Kristian 1991), upper limits of about 23rd magnitude on a pulsed signal in various bandpasses in the visible (Ögelman et al. 1990), and the finding of no pulsed energy in gamma rays greater than 0.75 Mev (Kerrick et al. 1991), in x-rays from (1 - 24) keV, (Mitsuda et al. 1988), or in the radio (Manchester 1988), where the fractional amplitude from 0.03 to 512 Hz was less than (10 - 40)%. We report here on broadband observations in an ultraviolet plus visual bandpass obtained with the High Speed Photometer on the Hubble Space Telescope between June 1992 and November 1993. We observed the target five times on four different epochs during this period of 520 days (see Table 1). We used the finding aperture (0.65 arcsecond effective diameter) and the F160LP filter on the POL tube, which is an ITT 4012RP Vidissector with a bialkali cathode on a Suprasil faceplate. The detector-filter combination was sensitive in a bandpass extending from 1600 Å to about 7000 Å (Bless et al. 1992). The time resolution in every case was 100 microseconds.

2 Observations

To point the HSP at the position of SN1987A, the telescope was first centered on a nearby $V = 12.5$ star, the position of which was taken from the Space Telescope Science Institute Guide Star Catalog. The HST was then offset to the measured position of SN1987A

(Girard et al. 1988; West et al. 1987). Based on our experience using the same offset procedure to observe the Crab pulsar (Percival et al. 1993) and pulsar B0540-69 (time-averaged $V = 22.7$), the telescope after the offset was pointed within 0.3 arcsecond of the position of SN1987A. No anomalies were noted in the HST engineering data during the acquisitions to indicate any differences between the acquisitions of SN1987A and the other pulsars. The measured count rates, when compared with the count rates we measured for the Crab pulsar and for B0540-69, match the $V = 18$ brightness of the SN1987A remnant around the epoch of the observations, further supporting the conclusion that we were pointing at the target. Based on Faint Object Camera images taken near the epoch of our first observations (Jakobsen et al. 1991; Panagia et al. 1991), the remnant had a luminous ring around it, elliptical in shape with axes 1.6 x 1.0 arcsecond. The closest background stars detected were 1.6 and 3.0 arcsecond distant from the remnant. Our 0.65 arcsecond observing aperture fit inside the light echo ring, but because of the 3 arcsecond point spread function of the telescope, some light from the ring did enter our aperture, as did a few percent of the flux from the nearer background star.

The variations in count rate seen in Table 1 are due to slight pointing variations arising from using different pairs of guide stars during the observing program. Similar variations were seen in our Crab pulsar observations, and match the predicted variations arising from sub-arcsecond variations in the position of the aberrated point spread function within our 0.65 arcsecond electronic aperture.

3 Data Reduction

The correction of HSP data sets to the Solar System barycenter is described by Percival et al. (1993). Briefly, each sample was assigned an arrival time in the rest frame of the HST by adding the product of the sample time and sample number to the estimated start time of the observation. The start time calculation was verified by observing the Crab pulsar and comparing pulse arrival times in the visible to those in the radio, and is accurate to within a few milliseconds in UTC; relative time of any two samples in the same data set is accurate to better than 1 microsecond. For each sample time, the geocentric position of the HST was derived from the definitive spacecraft ephemerides generated by the Flight Dynamics Facility at the NASA Goddard Space Flight Center and was used to compute the time of flight to the barycenter. The barycentric position of the Earth was derived from the JPL DE-200 Planetary Ephemeris. Each sample time was then adjusted by the time of flight. The data were then resampled onto a uniform barycentric time series with a 100 microsecond sample time by assuming each photon arrived at the center of its barycentric corrected sample interval. This procedure allows some 100 microsecond sample intervals to contain photons with arrival times separated by as much as 199 microseconds, but the photons in each sample interval are independent.

A serious data quality problem was discovered in the first data set, taken on 1992 June 2. An ACF analysis showed significant correlation at a lag of 8.6 ms, or 86 samples. HSP time series are broken up by the HST transmission system into *lines*, which contain a programmable number of samples. An artifact of the HST data collection system made the line length for this data collection 86 samples, matching exactly the lag at which the ACF showed a significant correlation. The data were corrupted when certain seventh lines had a few samples copied into the following line, i.e., some samples at the beginning of line 7 appeared in both lines 7 and 8, and so on for line pairs 15 and 16, 23 and 24, etc. This contamination was especially pernicious because of its subtlety. A mean flux of 73 counts per second results in a photon being detected in only about 1 of every 140 samples. The length of the "cloned" stretch of data tended to be only about 12 to 24 samples, so the corruption ordinarily resulted only in the copying of zeroes from one place to another. The autocorrelation analysis, in addition to being sensitive to the effect, has the advantage of putting all the spurious correlation into one bin in lag space. Other analytical techniques, such as Fourier analysis, do not respond so benignly to the effect. Investigation by both the HSP team and the Space Telescope Science Institute has failed to identify the cause of this corruption. It has been seen in only three other HSP data collections, each of which was taken with precisely the same sample time (100 microseconds) and near in calendar time (6 days) to each other. None of the other observations of SN1987A was afflicted with this problem.

4 Data Analysis

4.1 Autocorrelation Analysis

For each of the four observations, a search for a periodic signal with a period P in the range of 200 microseconds $< P <$ 10 minutes was carried out by a variety of methods. The autocorrelation function at lag l of a time series x_i is given by

$$acf(l) = \frac{1}{N}\sum_{i=1}^{N-l}\frac{(x_i - \bar{x})(x_{i+l} - \bar{x})}{s^2} \tag{1}$$

where N is the number of points in the time series, i is the sample number, and $\bar{x}$ and s are the mean and standard deviation of the time series, respectively. A periodic signal in the time series with $P \approx lt_0$, where t_0 is the sample time, manifests itself in the ACF as a local maximum in the value of $acf(l)$ at fixed intervals separated by l lags. The mean of $acf(l)$ is $-1/N$ and the standard deviation of an individual lag time bin about that mean is $N^{-1/2}$ for a time series with no periodic signal present having a random distribution of arrival intervals between counts (Chatfield 1989). The ACF's of all of our data sets exhibited no local maxima at levels above those expected from a random distribution of counts having the same mean and standard deviation as the data set. A typical ACF, that of the first half of the March 1993 data set ($N = 1.2 \times 10^7$) from $l = 1$ (P = 100 microseconds) to $l = 100$ (P = 10 ms), is shown in Fig. 1. No periodic signal is evident.

We then added 10 consecutive 100 microsecond samples together to form a time series with 1 ms resolution having one-tenth the number of samples as the original time series, and again investigated its ACF from $l = 1$ (P = 1 ms) to $l = 100$ (P = 100 ms). We also added 100 consecutive 100 microsecond samples together to form a time series with 10 ms resolution and investigated its ACF from 10 ms to 1 s, and likewise for 1000 consecutive samples (100 ms time resolution) to investigate the ACF from 0.1 s to 10 s. The 5 data sets in Table 1 each had 4 x 100 bins in lag space investigated, a total of 2000 independent lag bins. We found a total of 5 bins at the 3σ level or greater away from the mean, 3 positive and 2 negative. For a random distribution, the probability of an individual lag bin being 3σ or greater away from the mean is 0.0027, so we expect 5.4 such bins out of 2000 in data if there is no periodic signal in it, consistent with our results. The largest excursion from the mean was at -4.1σ, at a lag of 52 ms in the November, 1993 data set; the largest positive excursion was at $+3.6\sigma$, at a lag of 4.5 s in the November, 1992 data set. None of the positive excursions corresponded to a real signal because no significant correlation was present in the same ACF at integer multiples of that lag, a significant correlation existed at that lag in one data set only, and the data binned modulo the period corresponding to that lag exhibited no structure resembling any known pulsar pulse profile.

4.2 Power Spectrum Analysis

We also searched for a periodic signal in our data using power spectral analysis. We expressed the power spectral function (PSF) in terms of the normalized function given by Fisher (Fisher 1929; Shimshoni 1971),

$$g_k = c_k^2 / \sum_{j=1}^{m} c_j^2 \tag{2}$$

where c_k is the kth harmonic amplitude in the Fourier representation of the time series x_i, of $N = 2m+1$ points: $c_k = \sqrt{a_k^2 + b_k^2}$, where $a_k = (2/N)\sum_{i=1}^{N} x_i \cos(2\pi ki/N)$, $b_k = (2/N)\sum_{i=1}^{N} x_i \sin(2\pi ki/N)$, $k = 1, 2, ..., m$, and $\sum_{j=1}^{m} c_j^2 = (2/N)\sum_{i=1}^{N}(x_i - \bar{x})^2$. The significance of the peaks in the PSF can be estimated directly from their g value. The frequency space we investigated corresponds to periods between 200 microseconds (the reciprocal of the Nyquist frequency) and 10 minutes. Fig. 2 is a plot of g_k versus signal frequency near 219.97 Hz for the PSF of the first half (first 996 s) of the November 1993 data set. The peak shown is the most significant one found in all our data. Using the Fisher criterion, we find that a peak as large as that in Fig. 2 (or larger) occurs in the PSF of 0.5% of all time series having a random distribution of arrival intervals between counts with no periodic signal present (corresponding to a 2.8σ deviation from the mean). The period corresponding to this frequency is 4.546 ms. The data binned modulo this period (Fig. 3) exhibit a sinusoidal variation with phase of the 4.546 ms period, and has one phase interval, of width 5% of the period, containing a significantly larger count rate than expected from this sinusoid.

This data set exhibits some properties that are consistent with a periodic signal embedded in a background of noise. Power at the 219.97 Hz peak is the highest present in the data received at the satellite, although not significant at the 10% level. The data at the satellite folded modulo the 4.546 ms period show only a sinusoidal variation. Transforming the data to the barycenter increases the significance of the power at this frequency in the PSF and sharpens the peak in the trial pulse profile into a single phase bin. The first 996 s of the November 1993 data set was rebinned into 400 microsecond bins and the PSF recomputed. The power at 219.97 Hz was significant at the 0.15% level. We subdivided this data set by splitting the 996 s of data into two equal segments of 498 s each, corresponding to the first and second quarters of the full November 1993 data set. Two trial pulse profiles were generated from these subdivisions by folding each set modulo the 4.546 ms period. Each of these pulse profiles is similar to Fig. 3; in particular, the phase of the peak count rate bin is maintained, as is the general sinusoidal-plus-high-bin shape of the pulse profile. All of these characteristics are consistent with the behavior expected from a pulsar signal from the SN1987A remnant.

We cannot claim that this is the signal of a pulsar, however, because it lacks other characteristics of such a signal. The power in the vicinity of 219.97 Hz is contained almost entirely in the first half of the November 1993 data set, being close to the mean power in the PSF in the second half. (The mean count rate in the two halves of the November 1993 data set is the same within statistics.) Folding the second half of the November 1993 data set modulo the 4.546 ms period produces a flat distribution in phase with variations about the mean consistent with a random distribution. The power in the PSF for the entire November 1993 data set at this frequency is not significant at the 10% level of significance. No significant peak is seen at the corresponding lag time in the ACF of the first half of the November 1993 data set. No significant power appears at or near this frequency in the PSF of any other data set. In addition, the phase of photons arriving in those 100 microsecond samples having more than one photon in the sample during the first half of the November 1993 data set (486 photons in all) have a random distribution with phase and show no correlation with the phase of the peak or maximum of the sinusoid in Fig. 3. We conclude that the power at this frequency, and all the power we see at any frequency in the PSF's of all our data sets, are consistent with those produced by a random distribution having no periodic signal in it.

4.3 Frequency Smearing

Three effects may reduce the statistical significance of any periodic signal in our barycentric corrected data by smearing out the signal over adjacent bins in frequency space during a 40 min observation. These are (1) an increase in the pulsar period caused by its rotational energy loss over the duration of the observation; (2) Doppler effects caused by orbital motion of the pulsar about a second body; and (3) Doppler effects caused by the free precession of the pulsar.

Because $\dot{P} = -\nu^{-2}\dot{\nu}$, where ν is the frequency of the pulsar and P its period, the first effect produces a frequency change over interval Δt of $\Delta\nu = -\dot{P}\nu^2\Delta t$. For $P = 1$ ms, $\Delta\nu = -2.4 \times 10^9 \dot{P}$ over a 40 minute observation. If $\dot{P} = 4.2 \times 10^{-13}$, as for the Crab pulsar, then $|\Delta\nu| = 1$ mHz. The frequency interval in the PSF analysis is 0.4 mHz ($= 1/(Nt_0)$) and 0.8 mHz in the ACF analysis, so spindown should not seriously degrade the detectability of any pulsar with $P > 1$ ms if $\dot{P}$ is not significantly larger than that exhibited by the Crab pulsar.

For orbital motion (neglecting the question of what type of companion could survive the supernova event in a bound orbit), the average acceleration occurring over duration Δt that will not smear a periodic signal over more than one frequency bin is (Biggs et al. 1989)

$$a < \frac{2Pc}{Nt_0 H \Delta t} \tag{3}$$

where H is the order of the most significant harmonic in the signal. With P in ms, $a < 0.1P/H$ m/s^2 will not reduce the statistical significance of the signal. In the case of Keplerian orbital motion, close binaries with orbital periods less than one day exceed this average acceleration (e.g. A0620-00, where the orbital period is 7.8 hr, e = 0, and $a = 18$ m/s^2 (Biggs et al. 1989), but the effect should not significantly reduce the significance of any periodic signal in our data for binaries with orbital periods greater than one day, or for non-millisecond pulsars.

If free precession were a significant contribution to the motion of the neutron star, it would modulate the phase and amplitude of any pulsed signal. Free precession has never been observed in any pulsar, however, and for neutron stars it is expected to be both small in amplitude and long in period (months to years) compared to the duration of our observations (Jones 1988; Glendenning 1990; Suleymanova et al. 1994).

We searched our observations for frequency smearing attributable to these effects by summing the power in 2 to 32 consecutive frequencies in the PSF and searching for regions in the PSF where power was enhanced above the average. We also searched for signals that were not purely sinusoidal by summing the power in the PSF at every frequency with powers at the 2nd, 4th, 8th and 16th harmonics of that frequency. No power was found in any of these cases significantly different at the 1% level of confidence from that expected from a distribution of counts random in time.

4.4 Sensitivity

We tested the sensitivity of our analysis in two ways, by injecting test signals into our SN1987A data and by comparing our SN1987A observations with those of the LMC pulsar B0540-69. We added to the November 1993 data set a synthetic signal of period 60 ms and mean count rate 1.67 counts/s (i.e., one detected photon every ten 60 ms periods on average; the arrival time at the 60 ms period was chosen to occur randomly with 10% probability of success), and one of period 6 ms and mean count rate 16.7 counts/s. The 60 ms signal was detected in the ACF at the 13σ level of significance. A count rate of 1.67 counts/s in the F160LP bandpass corresponds to a magnitude of $V = 22.5$ for an object with a spectrum and reddening similar to the Crab pulsar. Assuming we could detect a signal at the 7σ level of significance, this result indicates that we would have detected a periodic signal $(13/7)^2 \approx 3.5$ times fainter than this in our data, corresponding to $V = 23.8$. The 6 ms synthetic signal was detected in the ACF at the 89σ level of significance, Under the same assumptions, the 60 ms signal gives a detection threshold of $V > 25$. We observed the faint (V=22.7) LMC pulsar B0540-69 (Boyd et al. 1995) with the same detector and bandpass used for SN1987A, and measured a time-averaged count rate of 10 counts/s, of which 16%, or 1.6 counts/s, was pulsed. We detected the periodic signal in the PSF at the 19σ level of confidence (see Figs. 4 and 5). The PSF detection is more significant than the ACF detection for B0540-69 because the roughly sinusoidal mean light curve of the LMC pulsar is better suited to Fourier analysis. The ACF is better suited to signals (such as our test signals) whose FWHM corresponds to one ACF lag bin. Using the 7σ detection criterion above, we derive an upper limit of $V = 24.9$. We conclude that if any stellar remnant of SN1987A is emitting pulsed radiation with $P > 1$ ms, its time-averaged V magnitude is fainter than about $V = 24$ at the Earth.

5 Conclusions

The detection of neutrinos from the supernova gives us an unambiguous signal that a gravitational collapse has occurred (Hirata et al. 1987; Bionta et al. 1987). A compact remnant of mass $\approx 1.4 M_\odot$ is consistent with the neutrino signal, reinforcing the expectation that there is a pulsar to be found (Burrows 1989). Our failure to detect a pulsar in the optical could be due to a variety of possibilities, which we may categorize in the following general classes:

- the remnant may have collapsed to a black hole, not a neutron star (Burrows 1989; Woosley et al. 1989).
- a neutron star formed, but it is not a pulsar. Too much material falling back onto the neutron star can quench the pulsar mechanism (Arnett et al. 1989; Hills 1983); too weak a magnetic field or the alignment of magnetic dipole and rotation axis would prevent the emission of a pulsed signal, although these latter two possibilities appears unlikely for theoretical reasons (Romani 1990; Ostriker & Gunn 1969).
- a pulsar formed, but the Earth is not in its beam pattern. In this case, the presence of the pulsar should be detectable through its effect on the surrounding nebula. Any currently active pulsar deposits less than 8×10^{36} erg/s in the remnant (Suntzeff et al. 1992; Kirshner 1992), compared to 4.5×10^{38} erg/s for the Crab pulsar, giving us no compelling reason to infer the existence of a pulsar.

- absorption of radiation near the remnant prevents us from detecting any pulsar. The optical depth of this absorption should decrease as the square of the time since the explosion if the expansion of the ejected material proceeds homologously. Our last observation occurred 2,446 days (6.7 years) after the SN event, when the expanding nebula should have become optically thin (Michel et al. 1987). Theory predicts that a newly formed pulsar with $P \approx 2$ ms should have a luminosity ≈ 0.4 times that of the Crab pulsar (Michel 1994). The Crab pulsar has a time-averaged $V = 16$ at a distance of 2 kpc; at the Large Magellanic Cloud (d = 50 kpc), the apparent magnitude of the Crab pulsar would be $V = 23$. Our upper limit for any pulsed radiation from the remnant of SN1987A implies that $> 94\%$ of the radiation from this theoretically predicted pulsar is being absorbed in the remnant's debris (i.e., the optical depth of the debris is > 2.7).

Unless there is some physical process involved that is not characterized by one of the mechanisms on this list, continued lack of detection of a pulsar in the remnant of SN1987A will force us to conclude that at least one of these possibilities is correct.

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Figure Captions

Fig. 1.

The autocorrelation function (Eq. 1) of the first half of the March 1993 data set, $N = 12\times10^6$. Each lag is one sample time, 100 microseconds; 100 lags = 10 ms. The $3/\sqrt{N}$ (= 3σ for a random distribution) excursion from the mean of the ACF is at ±0.00087; the highest peaks in this ACF are at the $\pm2/\sqrt{N}$ level. No significant correlations exist at any lag.

Fig. 2.

The power spectral function of the first half of the November 1993 data set, $N = 10^7$. Only the region around the frequency of highest power (at $\nu = 219.97$ Hz) is shown. The power is expressed in units of the normalized Fisher function (Eq. 2), where $g(\nu) = 4.14 \times 10^{-6}$. The probability of a peak this large occurring in the PSF of a random data set having the same characteristics of the actual data set is 0.5%. The reasons for rejecting this peak as representing a pulsar signal are discussed in the text. The dashed lines show the probability of exceeding certain values of $g(\nu)$ for a non-periodic time series with a random distribution of arrival times between counts.

Fig. 3.

The first half of the November 1993 data folded modulo the 4.546 ms period of the peak power in Fig. 2. 20 phase bins cover one period; the trial pulse profile is repeated twice for clarity. The mean count per bin is 3197 +/- 103.

Fig. 4.

The power spectral function for the LMC pulsar B0540-69 (V=22.7). These data were obtained with the same detector and filter as the SN1987A data. Only the region around the frequency of highest power is shown. The peak is significant at the 19σ level.

Fig. 5.

The autocorrelation function for the LMC pulsar B0540-69 (V=22.7). The data were re-binned from 300 microsecond to 3 ms samples. ($N = 1.2 \times 10^6$). Each lag represents 3 ms, with the pulsar's fundamental period of about 50 ms appearing at lag 16.7. The $3/\sqrt{N}$

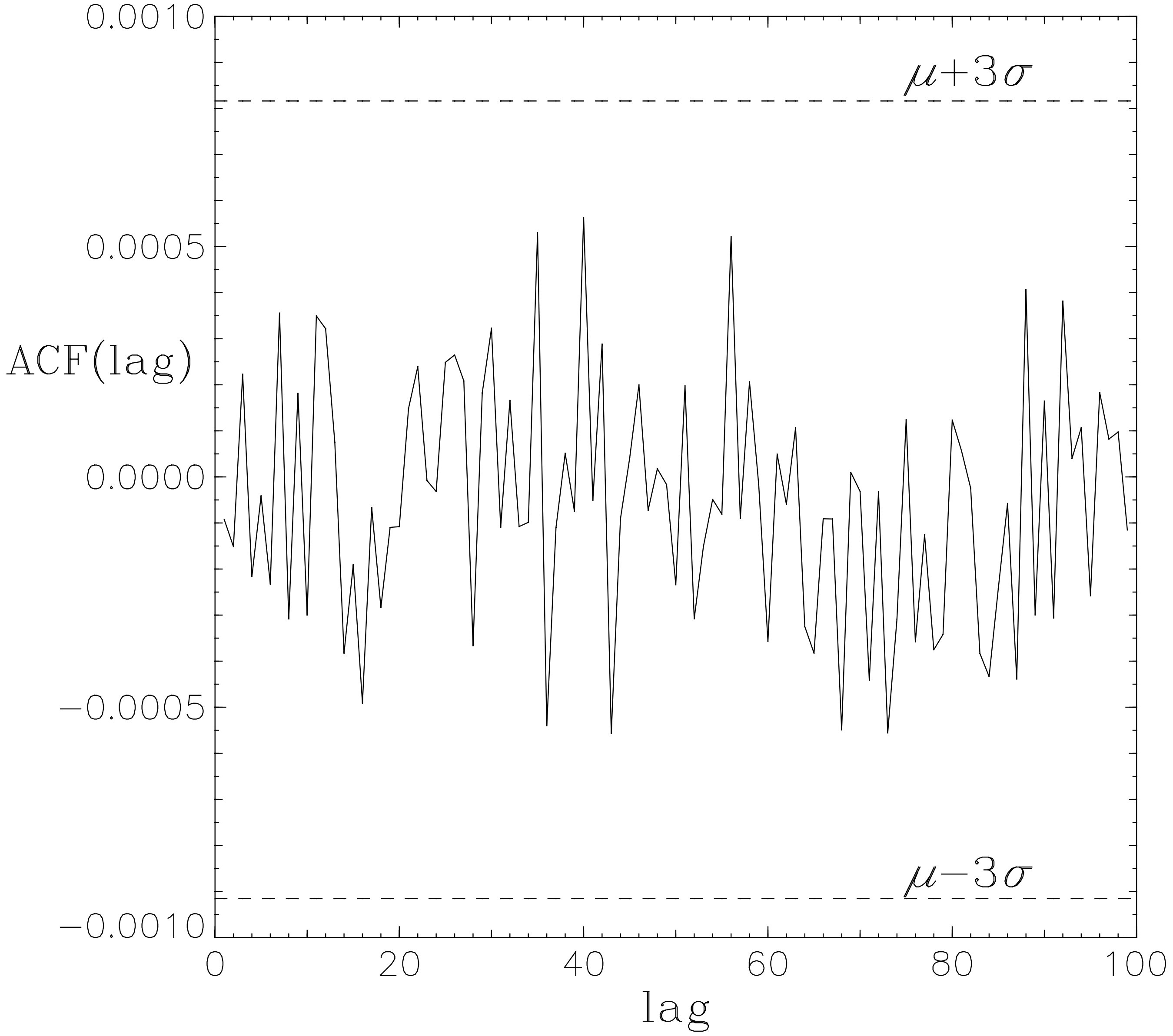
(= 3σ for a random distribution) excursion from the mean of the ACF is at ± 0.0027; the fundamental period is detected at lag 16.7 at the 3.5σ level of confidence. The ACF result is less significant than the PSF result for this object because the ACF is most sensitive to a pulse profile whose FWHM corresponds to one lag bin, while the PSF is most sensitive to sinusoidal signals. The mean light curve in Boyd (1995) is roughly sinusoidal, giving the advantage to the PSF.

UT date	start time (MJD[1])	Duration (s)	Mean flux (counts/s)
June 2, 1992	48775.460581	2400	72.68 ± 0.17
Nov. 22, 1992	48948.807753	2400[2]	88.91 ± 0.22
March 6, 1993	49052.906968	1200	99.82 ± 0.29
March 6, 1993	49052.966968	1200	99.74 ± 0.29
Nov. 4, 1993	49295.654135	2045	64.26 ± 0.18

Table 1: Observations of SN1987A

1. The tabulated start time is referred to the Solar System barycenter.

2. A temporary loss of lock in the HST fine guidance system made the first 560 s of this observation unusable.



0.0010
0.0005
0.0000
−0.0005
−0.0010
ACF(lag)
$\mu+3\sigma$
$\mu-3\sigma$
0
20
40
60
80
100
lag

Figure 1:

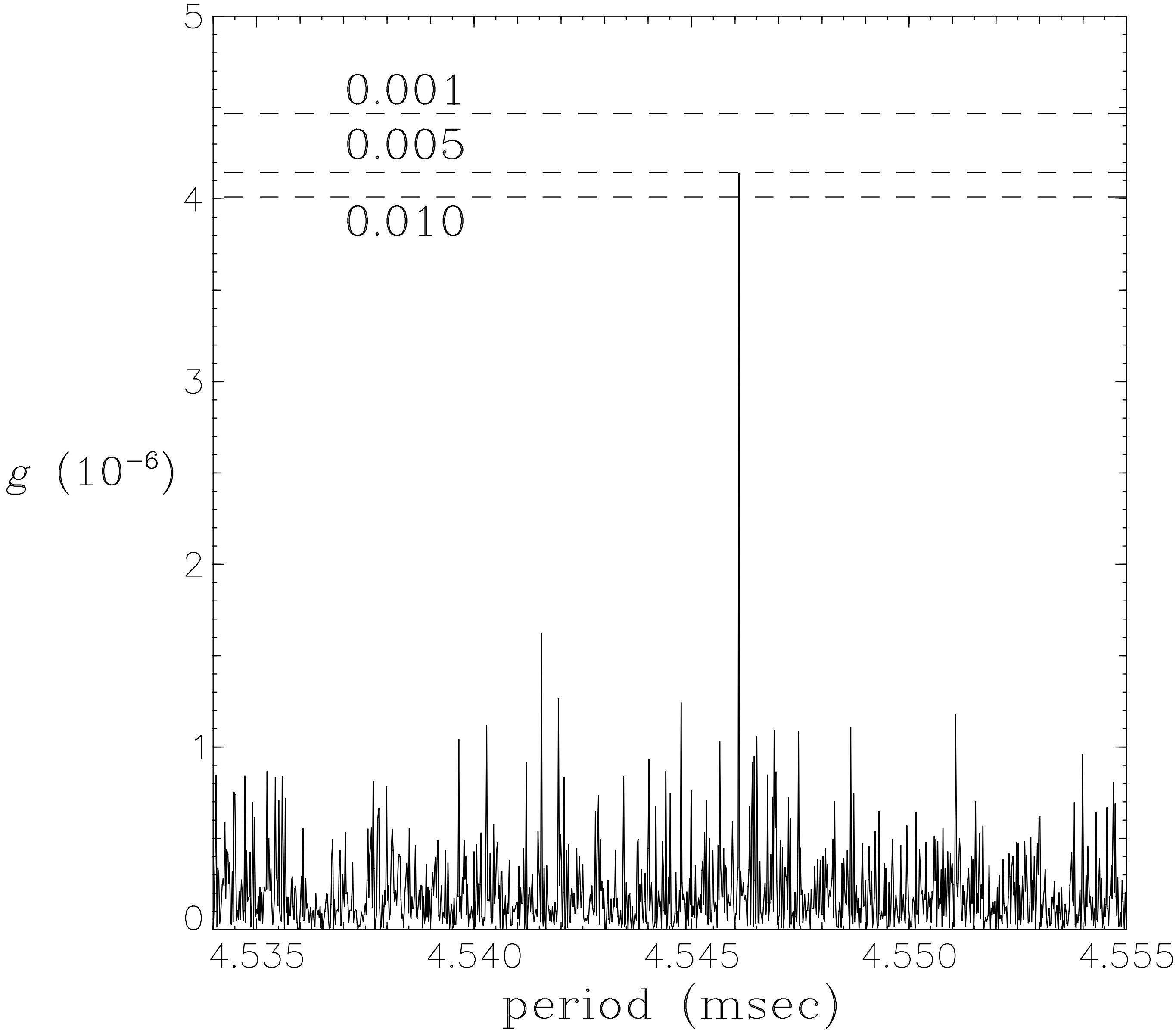

0.001
0.005
0.010
5
4
3
2
1
0
g (10^{-6})
4.535
4.540
4.545
4.550
4.555
period (msec)

Figure 2:

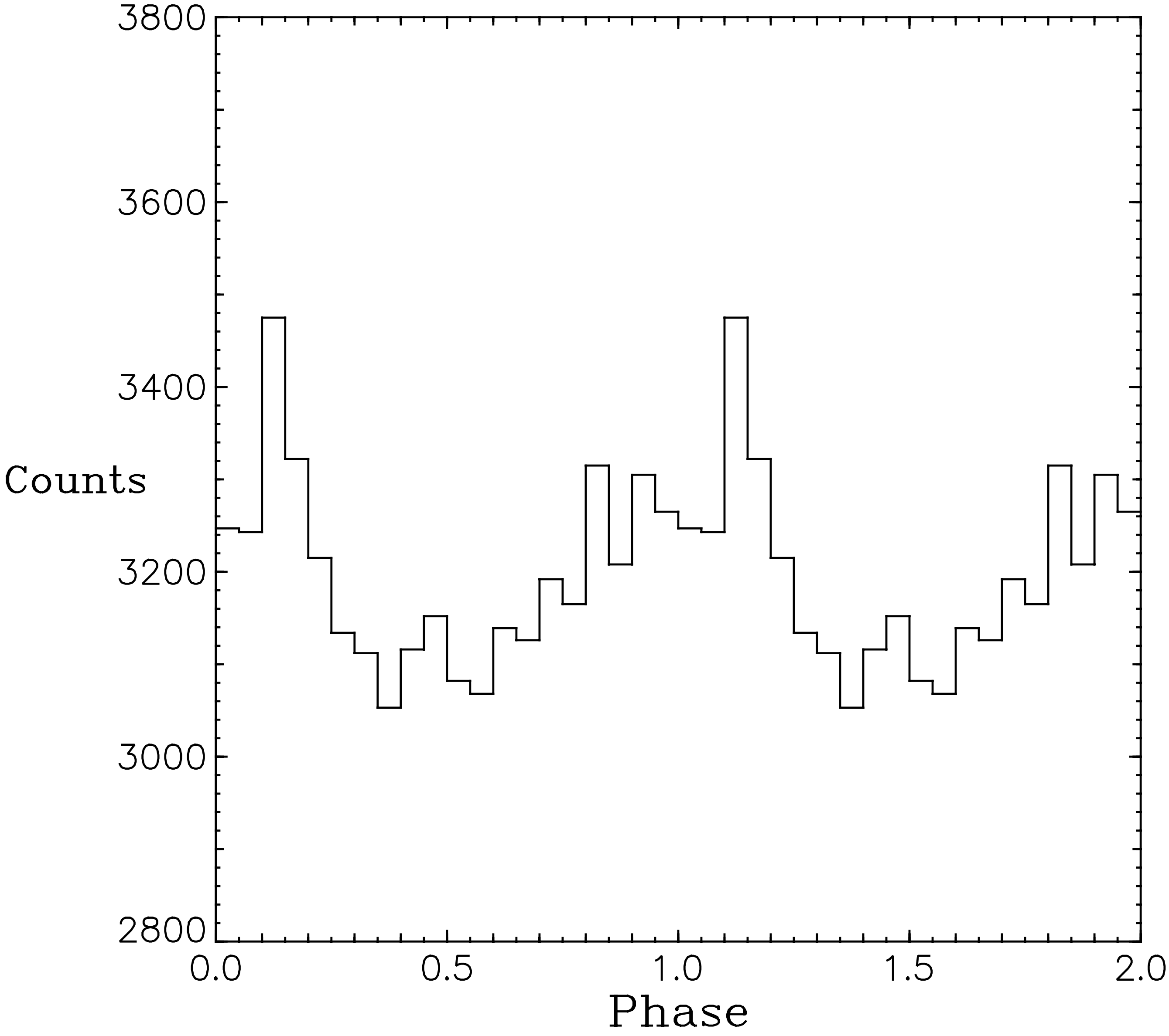
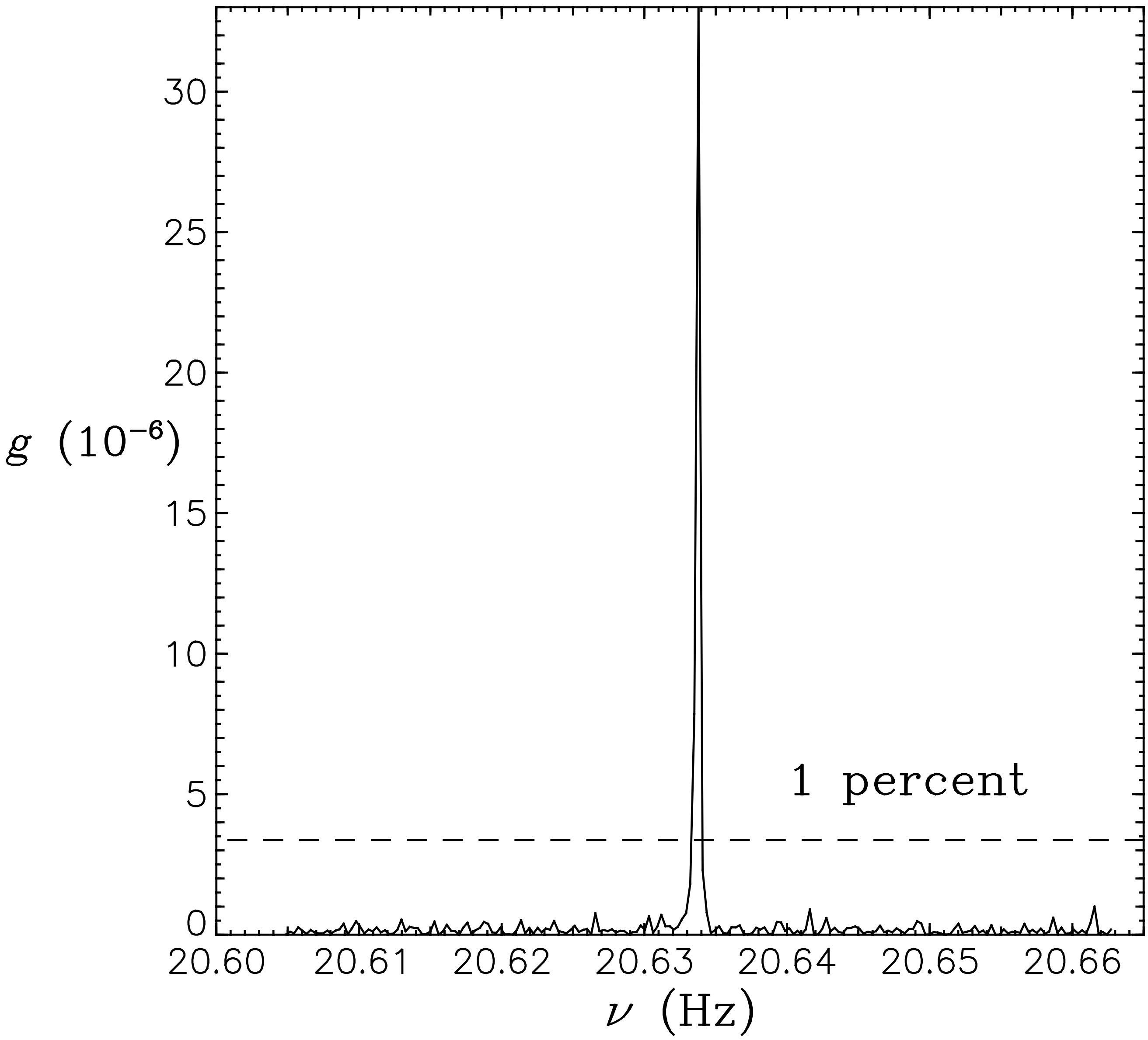


Figure 3:



30
25
20
15
10
5
0
$g\ (10^{-6})$
1 percent
20.60
20.61
20.62
20.63
20.64
20.65
20.66
ν (Hz)

Figure 4:

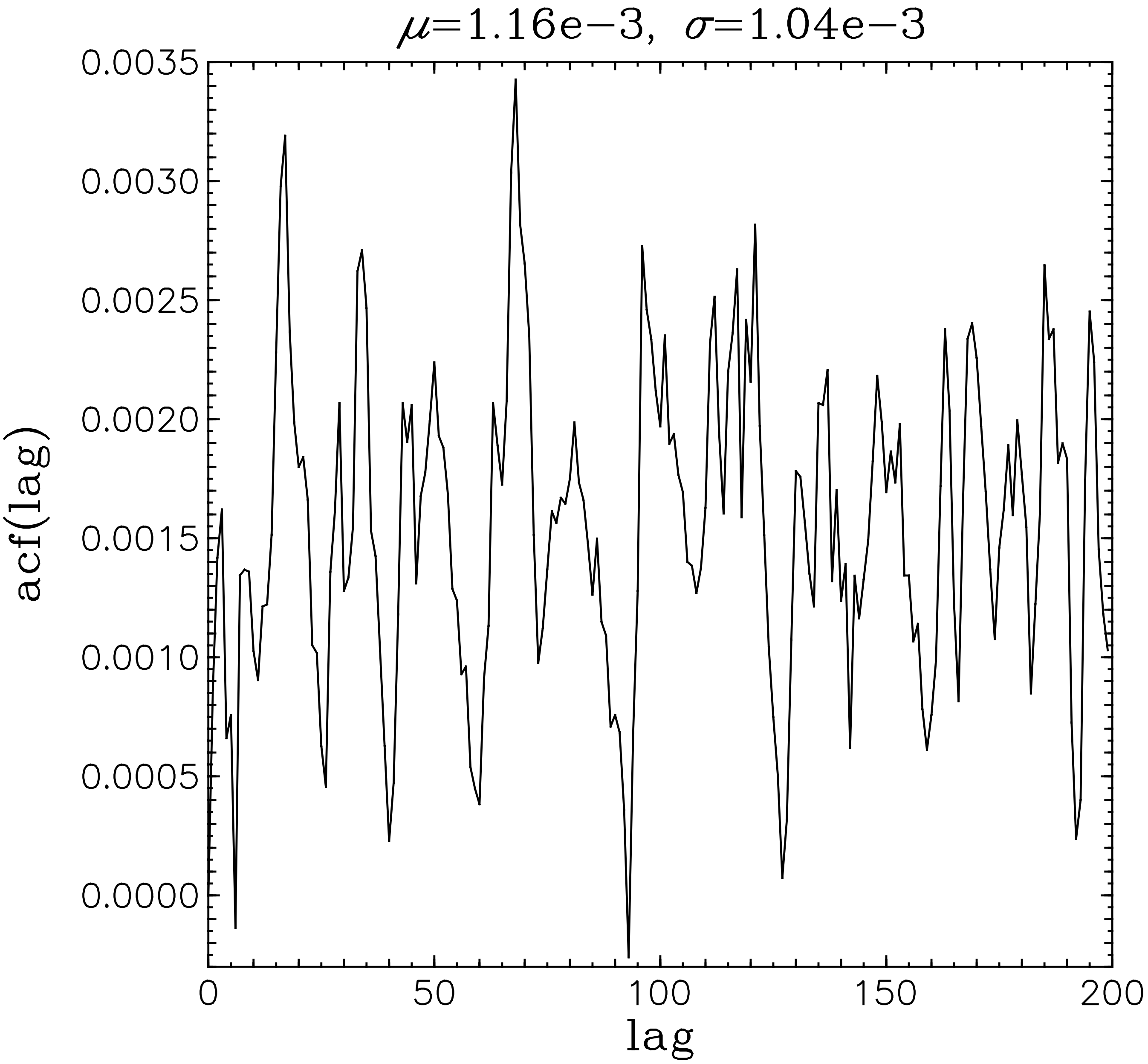

μ=1.16e−3, σ=1.04e−3
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
acf(lag)
0
50
100
150
200
lag

Figure 5: