REVERBERATION IN THE UV–OPTICAL CONTINUUM BRIGHTNESS FLUCTUATIONS OF MACHO QUASAR 13.5962.237

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ABSTRACT

We examine the nature of brightness fluctuations in the UV–Optical spectral region of an ordinary quasar with 894 optical brightness measurements made during the epoch 1993–1999. We find evidence for systematic trends having the character of a pattern of reverberations following an initial disturbance. The initial pulses have brightness increases of the order of 20% and pulse widths of 50 days, and the reverberations have typical amplitudes of 12% with longer mean pulse widths of the order of 80 days and pulse separations of an order of 90 days. The repeat pattern occurs over the same timescales whether the initial disturbance is a brightening or fading. The lags of the pulse trains are comparable to the lags seen previously in reverberation of the broad blueshifted emission lines following brightness disturbances in Seyfert galaxies, when allowance is made for the mass of the central object. In addition to the burst pulse trains, we find evidence for a semiperiodicity with a timescale of two years. These strong patterns of brightness fluctuations suggest a method of discovering quasars from photometric monitoring alone, with data of the quality expected from large brightness monitoring programs such as Pan-STARRS and LSST.

Key words: accretion, accretion disks – quasars: individual (MACHO 13.5962.237)

1. INTRODUCTION

Shortly after the discovery of quasars, brightness fluctuations of their UV–Optical brightnesses were discovered (Matthews & Sandage 1963). But while several important brightness monitoring programs were undertaken to observe such fluctuations with photographic and photoelectric photometry, little is yet known about the nature and origin of such fluctuations. Many studies searching for short-term inter-night and intra-night variability have been undertaken, especially for BL Lac objects, to put constraints on internal structure, possibly the inner edge of the accretion disk. We concern ourselves here with longer term variability because it would evidence the global structure of the quasar.

Among the first and most comprehensive studies was the publication by Hawkins (1996), based upon a sparse sampling (four observations per year). A more recent work (Hawkins 2007) incorporated an analysis of the MACHO quasars with structure function analysis and Fourier techniques not suited for the study of random events of the kind we find. Netzer et al. (1996) analyzed photoelectric photometry and looked for many correlations with quasar properties but did not find the reverberation signature. Webb & Malkan (2000) analyzed brightness fluctuations but on timescales too short to recognize the reverberation patterns that we find in our data, and Rengstorf et al. (2006) used structure function analysis for the detection of variability in large samples of stellar objects.

The existence of reverberation in the UV–Optical continuum was recognized already in 1997, and interpreted as indicative of a large quasar structure by Schild et al. (2006) in the comprehensively studied gravitationally lensed Q0957 (The First Lens) quasar. Following the earlier discovery by Thomson & Schild (1997) from autocorrelation analysis that strong repeat patterns of brightness fluctuations were seen over a long 20 year period of monitoring, these reverberations were combined with microlensing results to produce a picture of luminous structure that seemed to reinforce the picture of outer quasar

structure already found by Elvis (2000). In particular, the radial distance of the Elvis outflow structure matched the distance to the reverberating emission line structures found in the Seyfert galaxy NGC 5548 (Peterson et al. 1994) when allowance was made for the larger quasar mass. A refinement by Schild (2005) seemed to demonstrate that the pulse trains observed evidenced outer structure above and below the accretion disk plane, about as described in the Elvis (2000) model. A microlensing simulation showing that the inner and outer luminous structure is required to fit all available microlensing data was given by Schild & Vakulik (2003).

No physical theory is yet available to guide a discussion of such a large quasar structure as implied if the reverberations, observed on timescales of approximately 100 days, are produced by the collapsed central object and propagate to outer luminous structure at light speed. The broad, blueshifted high-excitation emission lines present in all quasars are presumed in standard theory to originate in clouds randomly orbiting the central structure. A unification model featuring absorption in a dusty torus has no physical basis in kinematic or dynamical theory, although it seems to be required to explain the outflow winds that are revealed in diverse spectroscopic data (Elvis 2000). Proga (2000) has developed a theory of line driving to explain the outward forces driving an outflow wind but no theory is available to explain why mass is observed so high above the accretion disk plane. However, the MECO model of black hole and quasar structure seems to offer a way for strong magnetic fields originating at the center to produce the uplift as a result of magnetic effects caused near the outer light cylinder (Schild et al. 2008). In this case, the central object would be radiatively inefficient (Robertson & Leiter 2006), much as standard black hole models also predict.

2. DATA AND PRELIMINARY PROCESSING

We have analyzed the data for the 59 quasars that are seen behind the Magellanic Clouds and which therefore had their brightnesses monitored during the seven-year duration of the MACHO microlensing project. A simple autocorrelation calculation immediately showed that they all had significant autocorrelation structure on timescales of several hundred days, and according to current theory such long timescale brightness fluctuations must either evidence systematic brightening of the small central source, whose light travel time size is less than a light day, or must originate in distant outer structure illuminated by the central region.

No theory for central structure nonperiodic oscillations with 100 day timescales is known to us. Reverberation between central and outer structures has been reported on relevant timescales in Seyfert galaxies (Peterson et al. 1994), when scaled from Seyfert to quasar masses. Thus, we have presumed that the effects we observe are the result of reverberation of the central continuum brightness fluctuations on the outer luminous region that has already been demonstrated by Elvis (2000) to originate the broad blueshifted emission lines caused by an outflow wind.

The data files that we analyzed are available at the Yale University Web site: http://www.astro.yale.edu/mgeha/MACHO. We immediately converted the brightness records tabulated in magnitudes to linear units, and removed the outlying data points exceeding 5σ . The brightness records were available from V and R color filters, but the V brightness records are significantly more complete, and we have not thus far analyzed the R data.

Our first processing step was to re-scale the timescaling, using an IDL procedure to divide the entire seven-year time interval into 894 time steps (tixels). Because data were taken on 894 nights, each tixel contains on average data for a single night. Any tixels with no data were linearly interpolated over. The time domain structure we are analyzing has a characteristic timescale of 70 days. Our longest interpolation interval is 55 days, and no other is nearly so long, and since our fueling function to be derived in Section 6 contains many pulse trains we may conclude that interpolation does not play a role in defining our measured pulse trains.

Following our preliminary autocorrelation calculation, we realized that approximately half of the quasars had significantly

more data points than the remainder. To minimize problems associated with interpolation, we restricted our attention to the half which have the most data, each with approximately 1000 observations. As we further analyzed the brightness data, we found a variety of unexpected behaviors, such as semiperiodicity and broad central autocorrelation peaks. Therefore, we have chosen to report on one particular quasar, MACHO 13.5962.237, which exemplifies the kinds of behaviors encountered, to allow us to demonstrate the analysis techniques employed. Our analysis of the complete sample showed that the reverberation properties displayed by our chosen quasar are shared by all the quasars, but the data are less compelling for a few objects with smaller data samples or with higher redshifts. We will show in a future report that the predicted pattern of reverberations seen in Section 4 is found in an automatic machine data processing. The redshift of our selected quasar is 0.17, and all results in this report are expressed in time units measured by an observer in our local reference frame.

3. SEMIPERIODICITY: AN UNDERLYING SOURCE OF LONG TIMESCALE VARIABILITY

Our initial procedure when confronting the MACHO quasar data was to compute autocorrelation for each of the quasars, since we expected to see the autocorrelation structure discovered in Q0957 by Thomson & Schild (1997). However, we noticed that for MACHO 13.5962.237 a much longer lag was seen to the autocorrelation minimum at 700 days, and that the broad central autocorrelation structure appears to show substructure as inflection points for the 150 day lags expected. Inspection of the original brightness record, Figure 1(a), showed that the largest brightness fluctuations were indeed long-term changes that had the appearance of semiperiodic change. In our Figure 1(a) plot of the brightness data, the peaks of the semiperiodic signature are at lags 200, 1600, and 2200 days. Correspondingly, minima of the brightness curve are at days 900 and 2000.

Significantly, the central autocorrelation peak also showed inflection points for lags at 170, 280, and 450 days.



Figure 1. (a) Plot of the original data for M13.5962.237 with a 150 day boxcar-smoothed version of the data overplotted as a double-weight line. (b) A simple autocorrelation calculation of the original data shows a significant autocorrelation bottom at 710 days. (c) When the boxcar-smoothed curve is subtracted from the original data, effectively filtering out the lowest frequencies, a plot of the high-frequency component dominated by reverberations is obtained. (d) The autocorrelation of the high-frequency component now shows a significant anticorrelation bottom at only 80 days, and a strong narrow central autocorrelation feature.

To look for the autocorrelation signal evidencing structure of the kind seen in Q0957, we subtracted off the semiperiodicity. Because no model exists for semiperiodic brightness fluctuations due, for example, to a relativistic orbiting hot spot, and because simple inspection of the heavy solid curve in Figure 1(a) shows asymmetrical profiles, correction with a simple function such as $A \sin(t)$ would not give a good representation and possibly leave worrisome artifacts.

Therefore, we adopted a simple procedure of removal by a kind of unsharp masking. The structure we are looking for should have a timescale of less than 300 days and the observed quasi-periodicity autocorrelation bottom is at 700 days. So we ran a 300 day boxcar-smoothed algorithm over the data to create a smooth representation of the longest term trends. The smoothed data are also shown in Figure 1(a) as a heavy solid line. The smoothed data were then subtracted from the original data to produce a brightness record dominated by fluctuations on timescales of interest for reverberation, Figure 1(c). Simple inspection of Figure 1(c) shows a pattern of sharp pulses with brightness amplitudes of approximately 15% and durations of approximately 50 days.

We next performed our autocorrelation analysis on the detrended data, with the results shown in Figure 1(d), where we clearly see a significant negative (anticorrelation) detection of 0.31 for a lag of 70 days. The profile of this anticorrelation peak is convincingly symmetrical. The anticorrelation peak is followed by several peaks of comparable width but lower (0.1) positive correlation amplitude. Of the ensuing peaks shown, only the first few are taken to be real, since the autocorrelation function is likely to be dominated by remnants of the semiperiodic variations on long timescales.

4. A SIMPLE MODEL FOR QUASAR REVERBERATION

In a previous study of the Q0957+561 A,B gravitationally lensed quasar, we found evidence for reverberation in the UV–Optical continuum brightness curves and attributed it to reflections (or fluoresces) off of the outer Elvis structure surfaces (Schild 2005; SLR06). From this simple model, we were able to determine the angle of the quasar rotation axis to the line of sight.

In Schild (2005) and in the absence of a full theory of brightness fluctuations created from reverberation of a central disturbance, the simple equations describing the sequence of pulse arrivals were presented and solved only for the Q0957 quasar. In this section, we show the full solution in the form of a plot that shows how the reverberation pattern varies with the angle of projection between the rotation axis and the plane of the sky.

The equations for the time lags to the four brightness peaks expected for the Elvis structure geometry with luminous regions above and below the accretion disk plane have been given in Schild (2005). A complication noticed therein was that the labeling of the reverberations $t_1...t_4$ depends on the angle, since for pole-on geometry the second reverberation is from the far side of the upper Elvis surface, but for equator-on geometry the second reverberation comes from the near side of the lower Elvis surface. Schild (2005) called these case 1 and case 2 geometry. For the purposes of the general case illustrated in Figure 2, we have simplified the discussion and we simply identify the four reverberations with the equations written in the following form:

$$t_1 = r(1 - \cos[\theta - \epsilon]),$$

$$t_2 = r(1 - \cos[\theta + \epsilon]),$$

$$t_3 = r(1 + \cos[\theta + \epsilon]),$$

$$t_4 = r(1 + \cos[\theta - \epsilon]).$$

In Figure 2, we show the plot of reverberation times for the four reverberations seen in quasar brightness histories. For the purposes of this report, we adopt a value of 13 degrees for the small internal quasar structure variable ϵ , since 13 degrees is the value determined for the two quasars for which the reverberation has already been observed (Schild et al. 2006, 2008).

We will see in subsequent sections that the central quasar structure presumably causing the starting pulse is apparently

Expected pulse train from varying viewing angles 100 Viewing angle (degrees) 80 60 40 20 0 200 400 800 -200 0 600 Proper lag time (days) Expected pulse train for 60 degree viewing angle 1.0 Relative brightness 0.8 0.6 0.4 0.2 0.0 -200 200 400 600 800 Proper lag time (days)

Figure 2. Upper panel: a plot showing the order of reverberation pulses expected as a function of the viewing angle (between the plane of the sky and the axis of rotation) of the quasar. The sharper initiating pulse is shown as a triple-weight line at t = 0, and subsequent broader fainter pulses of reverberation follow at the times shown. For quasars viewed along their equators, the viewing angle is 0 and the initial pulse is broader because it occurs at the same time as the reverberations from the nearest two surfaces. A horizontal line at a viewing angle of 60 degrees shows how the plot would be read to show the pattern of reverberation features expected. Lower panel: we show the pulse train expected for a quasar inclined at 60 degrees, according to the structures computed in the upper panel. The amplitudes of the secondary pulses will vary as a function of viewing angle, and are shown all the same in the cartoon for simplicity.



Figure 3. Data segments co-added to define the shape of the waveform from reverberation. Six data segments are co-added to form the mean waveform shown as the solid heavy curve in all panels.



Figure 4. Six data segments co-added as in Figure 3 but for the negative-going reverberation pulse shapes, with the mean waveform shown as a solid heavy curve. The large diversity of brightness curves results not from observational noise, but from overlapping of the many pulse trains. The data have been plotted inverse to the observations, meaning that the fading pulses have been shown as positive, to allow simple comparison to the positive pulse waveform. Vertical lines show the lags where inverted structure may be present between the brightening and fading mean waveforms.

small, with a size parameter estimated from the (half-)width of the central pulse of only 25 days. The reverberations have typical time widths of 80 days and are separated by typical times of 100 days.

The curves in Figure 2 show behaviors that are qualitatively distinctive depending on the orientation of the quasar rotation axis to the plane of the sky. For quasars seen pole-on (viewing angle 90 degrees), an initial brightening of the central region (near to the inner edge of the accretion disk) will be followed after some months by the brightening of the nearest ring, and then by the farthest ring. For equator-on orientation, with the rotation axis lying in the plane of the sky, the initial central pulse is followed almost immediately by the brightening of the nearest surfaces and, after a long lag, by brightening of the distant surfaces. For an intermediate orientation, say 45 degrees, the four reverberations are well separated in time and can be individually recognized easily, as has been found for Q0957 where we have determined a viewing angle of 54 degrees (SLR06; Schild 2005).

The curves showing reverberation in Figure 2 are shown having a width (fuzziness) approximately equal to the expected pulse width. So for a quasar with a viewing angle of 60 degrees, shown as the horizontal line in Figure 2 (upper panel), we show in Figure 2 (lower panel) the pulse train expected. An initial pulse of 25 days (half-)width is followed by four additional pulses having 80 day widths in the pattern shown. The reverberation pulse amplitudes will be a complicated function of the outflow wind geometry, and our Figure 2 (lower panel) cartoon of the predicted pulse train arbitrarily shows the pulses equal in brightness.

We have made an approximate solution for the orientation angle on the sky for MACHO Quasar 13.5962.237. Although the equations for the reverberation structure given in Schild (2005) are overconstraining, in the sense that there are four equations for three unknown parameters, we find that a solution exists at 72 degrees for the four autocorrelation peaks identified from the Figure 1(d) plot. The same autocorrelation estimate is found plotted to larger scale in our final plot of comparison to



Figure 5. Upper panel: a comparison of the positive (solid heavy curve) and negative (light curve) mean wavelets, demonstrating the inverted structure for lags 80 and 115 days (vertical lines). This quasar was selected as an excellent example of such inverted structure, found in only 20% of the quasars. Lower panel: the waveforms are shown again, but with the correct sense of brightening and fading pulses preserved.

simulated data. We do not estimate a formal error bar because the errors are apparently systematic, relating to small asymmetries in the profiles of the pulses seen in autocorrelation. However, we suspect that from the agreement of solutions for various assumptions about the determinations of the pulse centers that the true internal error of the determination is approximately 3 degrees. Because there are probably systematic sources of error in our inclination angle determination due, for example, to the exact curvature and illumination of the reverberating Elvis surfaces, we consider a fair estimate of the inclination angle error is twice 3, or 6 degrees.

5. DETERMINATION OF THE PULSE TRAIN FOR REVERBERATION STRUCTURE

The positive autocorrelation peaks calculated from the brightness data are of low amplitude, but are probably real. Since the original data defining a single 70 day wide peak would contain on average 23 data points, each with a 1σ error of 0.03 mag, an entire peak has a significance exceeding 10σ .

We have used a "poor man's autocorrelation" technique to reveal the nature of the reverberations. In Figure 3, we have coadded the data segments following the central structure peaks that we can easily identify in the Figure 1(c) brightness record. We have not included the wave trains following several of the peaks, especially in the cases where the peaks are double or ambiguous. In the data segments in Figure 3, we have placed the central brightness peak at 70 days, to see the average brightness preceding the peak in case there are any precursors (which we do not find). In each panel of Figure 3 (and of Figure 4), we show the individual wave trains following the initiating pulse. For comparison, the mean wave train formed by averaging the six contributing wave trains is shown as a heavy solid curve. This mean curve shows by construction the mean profile of the initial pulse and the ensuing pattern of reverberations. The initial pulse has a mean average of 0.3 mag, or 30% brightness peak, and a pulse (half-)width of 50 days. This is followed on timescales of approximately 100 days by secondary, or reverberation, pulses, of comparable widths but lower, 0.10 mag or 10%, brightness increase. We do not know of any model that could generate an error statistic for the mean waveform computed, because noise

in this mean waveform determination is physically caused by their overlapping.

Simple inspection of Figure 1(c) also shows important events where the quasar brightness *faded*, with the amplitudes and durations of the fading events comparable or slightly smaller than the brightening structure. Such events have never been predicted by theoretical work. The existence of such events—and their characterization—must necessarily be ambiguous to some extent because our methodology includes referring all fluctuations to the long-term mean quasar brightness. Nevertheless, the fact that we find similar pulse train lags for the fading and brightening events shows that they have some reality, with future quantitative refinement of our analysis method still needed.

In Figure 4, we show the procedure for averaging data segments for individual fading event pulse trains analogous to Figure 3. In particular, the peak fading is again set at 70 days to allow inspection for a precursor. However, in Figure 4, all the data have been sign inverted to make the pulse trains look like our brightening pulse trains in Figure 3. It will be immediately recognized that Figure 4 pulse trains have surprising similarity to the positive pulse trains in Figure 3. In particular, we find that the central structure has a slightly lower mean amplitude but a similar pulse width. The later arriving pulses have the same width as in Figure 3, and are separated by comparable lags.

However, an important difference is found between the pulse trains following central brightening and fading events. We show in Figure 5 a comparison between the two mean pulse trains measured. In the comparison, we find evidence for an *inverted structure*. This means that when the quasar brightens at a reverberation site for some lag relative to a central brightening, the quasar also *brightens* at the same lag for a central fading. Such inverted structure may be seen in Figure 5 at lags of 82 and 115 days (shown by the vertical lines in Figure 5). The 82 day pulse in the two waveforms seem to agree well in pulse width and amplitude (Figure 5, lower panel). However, for the 115 day lag, it is not obvious if there is a real inverted structure or just a difference in waveform, possibly caused by noise in the mean waveform determination.

In some ways, it may have been counterproductive to analyze a quasar selected to show the full catalog of brightness variability behaviors. The resulting report has a remarkable list of unexpected behaviors needing explanation and even though the data quality is excellent and does not limit any of the interpretations, the complexity of the phenomena does. Thus, we present Figure 6 with a view toward bringing together several phenomena explored.

In Figure 6, we show the brightness records of the mean wave trains determined for the positive and negative spikes in comparison with the Figure 1(d) autocorrelation calculation. The solid heavy line represents the autocorrelation, and the thin line represents the mean of the positive and negative pulse means. In other words, Figure 6 is a comparison of the pulse trains estimated from autocorrelation with the mean pulse train averaged from the many data segments. The purpose is to show the similarity of the autocorrelation properties to the structured brightness trends.

In Figure 6, the full width to the first zero of the autocorrelation curve is at approximately 25 days. The zero crossing of the mean waveform curve occurs for a comparable lag. Thus, the width of the initial brightness burst is measured to be about the same, 25 days, for both techniques.

Summarizing our comparison of the autocorrelation estimates with our attempts to identify the specific waveform of the



Figure 6. The mean reverberation waveform from averaging the positive-going and negative-going waveforms, compared with the autocorrelation function for the high-frequency data.



Figure 7. Determination of the fueling function as the cross-correlation of the mean reverberation waveform against the low-pass filtered brightness record.

brightness fluctuations, we would say that we have found a mixed picture. While it seems likely that a sharp 30% brightness spike of 25 day width precedes a pulse train extending over a year, the problem of overlapping of these wave trains makes difficult their clear representation and frustrates any attempt to estimate an error bar. The different kind of wave train for pulses of fading brightness may have related form. In particular, at the two lags where the brightening and fading wave peaks have inverted structure, the autocorrelation estimate has near-zero amplitude.

Nevertheless, it is clear that some kind of structure is evidenced in these pulse trains of year-long duration. Because the standard black hole model of quasar structure does not include any luminous regular structures with length scales longer than a light day, the study of such repeating or quasirepeating brightness features on year-long timescales is new information about the nature of the luminous quasar structure.

Although it might seem obvious that a brightening of quasar structure would reverberate around the quasar as lagging brightenings, this is not necessarily the case, and Gallagher & Everett (2007) have suggested a mechanism that might produce negative reverberation.

6. THE QUASAR FUELING FUNCTION

In Figure 7, we show the amplitudes and lags of the quasar brightness pulses determined as the cross-correlation of the mean pulse train profile estimated in Section 5 with the semiperiodicity-corrected brightness data illustrated in Figure 1(c). With the interpretation that the pulse trains illustrated in Figures 3 and 4 represent the ordinary quasar brightness fluctuations resulting from its fueling, the results in Figure 7 are effectively the quasar fueling function. Recall that the curve in Figure 7 has been set against a zero mean.

The results in Figure 7 seem to show that the quasar fueling is a reasonably stochastic process with a train of pulses having similar brightness amplitude and duration during the seven-year period of observations.



Figure 8. A noise simulation for the autocorrelation function, from data created by scrambling the lags in the table of observations. The simulated noise calculation has been processed with the same noise averaging and smoothing before autocorrelation. Compared to the autocorrelation calculated for the real data, plotted as the heavy solid line, the simulated data show qualitatively lower amplitude of autocorrelation and structure on much shorter timescales.



Figure 9. A simple data plot (upper panel) showing the magnitudes of a field star in the vicinity of the quasar. In comparison, the quasar brightness record (heavy curve) contains many small features of amplitude approximately 0.1 mag and duration approximately 70 days that are not seen in the record of field star brightness. In the lower panel, autocorrelation functions of the quasar (heavy curve) are compared to the field star. The quasar autocorrelation peaks are qualitatively larger in amplitude and duration. Particularly the first autocorrelation minimum occurs for longer lag and has larger amplitude than for the field star.

7. NOISE SIMULATIONS

Because of the complexities of the brightness phenomena that we are discussing, and particularly because no model of these effects is yet available, it is difficult to imagine a thorough simulation of the results obtained in the context of random noise. However, we have undertaken the two simplest kinds of simulations to make some approximation to the effects of random noise.

Our first simulation was made by simply scrambling the data points randomly onto the observed observation dates, to produce a noise data set related to the set we have been analyzing, and producing a boxcar-smoothed version of our simulated data and subtracting it as in the analysis of the real data. This produced very noisy plots of autocorrelation which reached a peak anticorrelation value of -0.1 (instead of our comparable observed value of -0.31) and a significantly different appearance of the autocorrelation peak. The peak in the simulation was significantly narrower, at about 10 days width,

which is the effective resolution of our data. Ten realizations of this randomizing of the data points produced similar results that did not look like our real data products.

In Figure 8, we show a typical plot of the noise simulation for the quasar data with red noise suppressed exactly as was done for our real data. The solid curve is the autocorrelation computed for real data. It may be seen that the two are qualitatively different, with the quasar data showing quasar brightness fluctuations on timescales much slower than the effective sampling, whereas the noise data show twinkling at lower amplitude and higher frequency.

We have undertaken a further simulation which is related to the observational noise properties of the MACHO data set. It is well known that there are noise effects related to seeing effects and extinction effects plus processing errors for plate solution, etc. These errors are presumed to affect PSF-fitting procedures for all the stars in an individual field. Thus, estimates of magnitude for stars and quasars in an individual field should have very similar noise characteristics, especially if the star and quasar have approximately the same brightness.

So we have examined the brightness records of several stars in the same field ("tile") as the quasar, and performed the same analysis as for our quasar. We show in Figure 9 the comparison of the simulation for the first star examined. In the upper panel of Figure 9, we simply plot in magnitudes the brightnesses of the two objects, and it may be seen quantitatively that the quasar has a larger level of brightness variability. Note that in this figure, we plot the data in magnitudes relative to their mean, to reduce the two brightness records to similar scale. It may be seen in this figure that the many small brightness spikes having amplitudes approximately 0.1 mag and durations of approximately 50 days are not found in the star data.

Finally, we show in Figure 9 (lower panel) the autocorrelation function computed for the field star and for the quasar. The autocorrelation peaks that we have analyzed in this report are obviously much stronger than in the field star. And the first autocorrelation minimum for the field star occurs near 5 days, the minimum sampling used in our analysis, whereas the minimum occurs for 70 days in the quasar. We have found that the data for the field star contains a small signature of the one year seasonal effects expected for observations of a circumpolar field.

8. CONCLUSIONS AND DISCUSSION

We have found that the MACHO program observations of quasar brightness are an excellent resource for the study of brightness fluctuations, because the fields observed are circumpolar and do not suffer from seasonal dropouts and produce results independent of the procedures of interpolation. From our autocorrelation analysis of 29 of the best-studied cases, we have found that fluctuations seem to have interesting characteristics on two major timescales. A future report, in progress, will show that the properties found here are common to all quasars.

On the longest timescales, of the order of two years, the fluctuations seem to have a quasi-periodic character with amplitudes of the order of 30% brightness change. They are not well represented by sine (t/500 days) but nevertheless seem to have a quasi-regular structure. We have analyzed one of the quasars showing this structure and investigated further the structure seen on much shorter timescales. Although it may be premature to call the large overall brightness structure semiperiodic on the basis of the data for MACHO 13.5962.237, similar structure has already been seen in the much longer brightness records for the Q0957 quasar (Pelt et al. 1998; Figures 1 and 2). Though seen at a larger redshift, three such peaks with comparable 0.3 mag amplitude and reasonably uniform cadence have been seen.

After removing the quasi-periodic overall structure, we have found that the autocorrelation properties evidence complex and reasonably regular structure having the character of a sharp central pulse followed by broader secondary pulses of lower brightness. The pulses are surprisingly similar for these rapid events whether the quasar is brightening or fading.

It is worth stating even though not proved herein that all of the 29 quasars for which we have analyzed brightness data evidence structure on 50 day timescales and some additionally on multiyear timescales. Thus, large scale structure with associated size scales of a light year appear to be a universal property of quasars. Because the tentatively observed reverberations have been associated with the previously discussed region where the quasar-defining broad high-ionization blueshifted emission lines originate, it appears that only a fraction of the dominant UV–Optical emission of quasars comes from the central region understood theoretically.

Our results suggest a technique for discovering quasars from large area photometric surveys presently being planned (Pan-STARRS, LSST). Calculation of autocorrelation of photometric brightness curves will reveal a signal with anticorrelation bottom of at least -0.2 for quasars. It remains to undertake simulations of data sets at various noise levels and observational epochs to establish the limits of effectiveness of this quasar discovery technique.

Such photometric monitoring has the prospect of not only discovering quasars, but also of directly determining masses. Establishment of the fundamental plane for MECO quasars by R. Schild et al. (2009, in preparation) seems to show that measurement of the bolometric luminosity and a reverberation-measured size parameter related to the distance of the quasar's light cylinder, or to the size of the inner edge of the accretion disk, allows the mass of the central object to be determined.

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