COSMOLOGY WITH GRAVITATIONAL LENSES: TIME DELAY AND MICROLENSING

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ABSTRACT

Astronomers study quasars, the enigmatic luminous black hole cores of distant galaxies, because of their huge distances; they sample the universe when it was only 1/10 of the present age. In about a dozen known cases, a random galaxy along the line of sight causes the quasar's image to be double or multiple, providing cosmologists with a tool for study of young galaxies and the structure of space and time itself. In these gravitational lens alignments, the images do not arrive at the same time, and measurement of the quasar's irregular brightness fluctuations allows determination of the light travel time differences.

For the first discovered gravitational lens, Q0956+561 A,B a 15-year data record of brightness fluctuations (Schild &Thomson, 1995) has been analyzed for time delay. Bad weather, telescope availability, and seasonal effects cause sub-optimal data sampling, but all time scales from a day to 15 years are reasonably sampled. We find the cosmologically interesting time delay to be 405 +/- 10 days, implying a universe about as old as the oldest known stars. Complications to the data analysis come from our discoveries that the quasar has internal structure in the form of reflecting regions, and planetary mass objects in the lens galaxy introduce additional brightness fluctuations. The quasar also shows periodic variability at multiple frequencies, probably due to oscillations of the luminous disc surrounding the black hole.

1. INTRODUCTION: QUASARS AND BLACK HOLES

The physics of quasars is poorly understood even though they have been actively investigated at all wavelengths since their discovery in 1964. A black hole with a mass of a billion suns is inferred to be the central energy source, with a surrounding disc of accreting matter probably present because infalling matter from the host galaxy has to shed some angular momentum before dropping upon the central mass. This accretion disc probably converts x-rays and gamma rays emitted by the black hole into ultraviolet and visible photons, and must be a swirling sea of gas rotating at relativistic speed. This is surrounded by gas clouds at light-year distances which further convert ultraviolet photons into visible light, with emission lines from light elements indicating strong chaotic motions.

One principal reason why these objects remain enigmatic is that they all lie at large distances. None is found in a catalogue of the million brightest galaxies, and astronomy must rely upon inferences from scanty observations to study these fascinating objects, which also stretch our fundamental knowledge of relativity and black hole physics.

2. THE DATA SET

The original motivation for monitoring the source was to measure the time delay between the arrivals of the two images. The physics of the interaction of the propogating quasar light with the gravitational field of the lens galaxy is adequately described by the general theory of relativity, and when the time delay is measured, the system of equations describing the interaction becomes closed, so that measurement of the redshifts of the quasar and lens galaxy, together with measurement of the image separation and the time delay, gives the distance to the quasar in kilometers (Falco et al, 1991). This distance measurement can be combined with the redshift measurement to determine the Hubble parameter, which is the basic scaling parameter of the universe which also tells how long the universe has been expanding since the big bang.

Quasars are expected to show brightness fluctuations on time scales of months, and the brightness has been sampled once nightly as telescope time permits. From the start, it was found that in fact nightly brightness changes of a few percent are observed, but variations within a night are not detectable. Therefore, data are collected and reported as a single brightness measurement of the two image components for each calendar date. Unfortunately, weather interferes and no major telescope can be entirely dedicated to such a project. Moreover, faint

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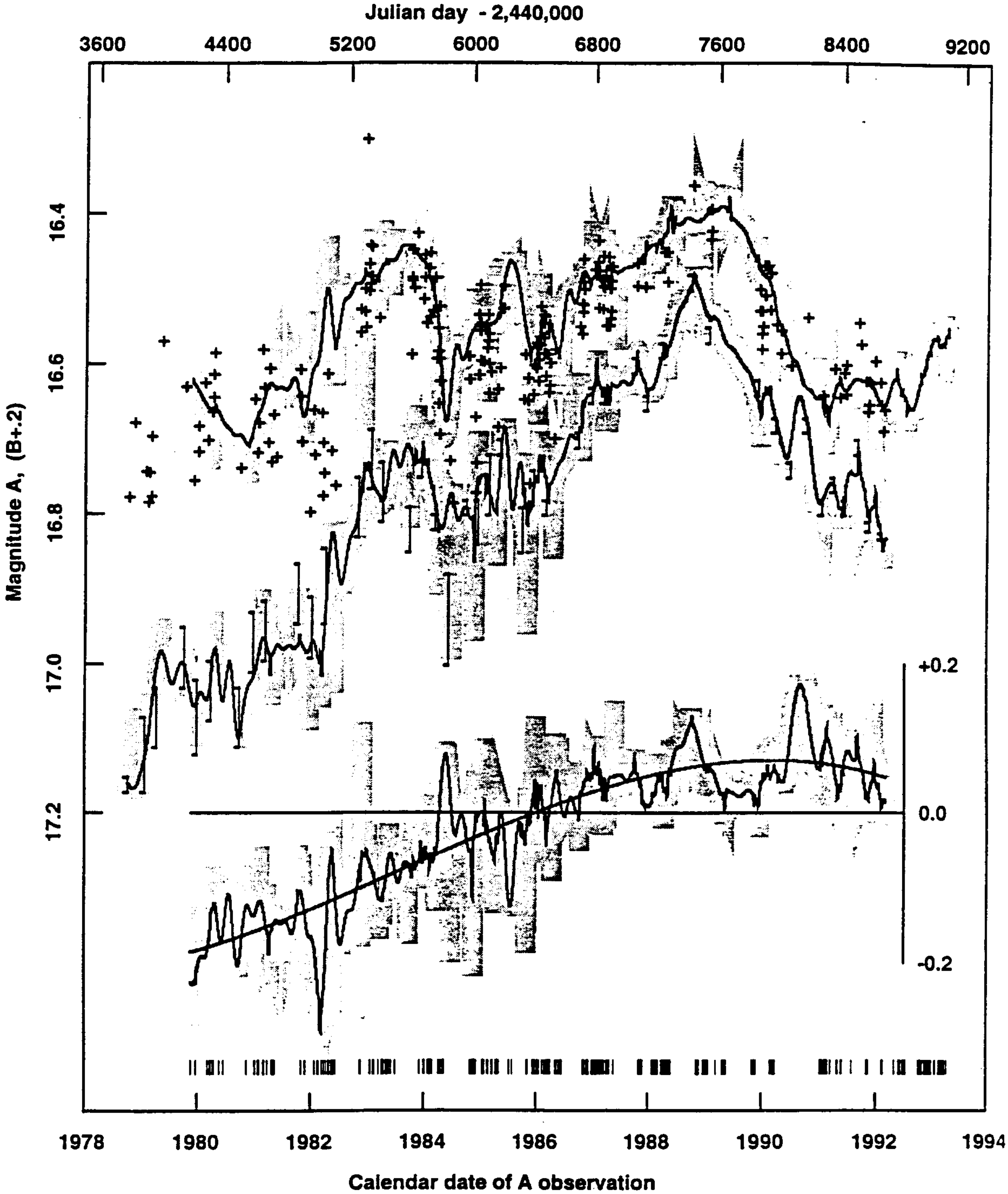

Figure 1. Top curve: The interpolated A brightness record, plotted as a function of observation date. The curve has been smoothed by runnung a trimmed mean for plotting purposes, with the unsmoothed range shown by the grey band. Center curve:The interpolated B brightness record, shifted by 0.2 magnitudes and advanced in time by 405 days. Error bars are shown for a few samples. Lower curve: The difference between A and B, smoothed by a runnung 5 point trimmed mean. The superimposed smooth curve is a cubic polynomial fit. The scatter plot superimposed upon the A brightness curve shows the B observations plus the cubic polynomial. Only 221 of the original 830 points are shown. The "rug plot" at the bottom marks the dates when observations were made.

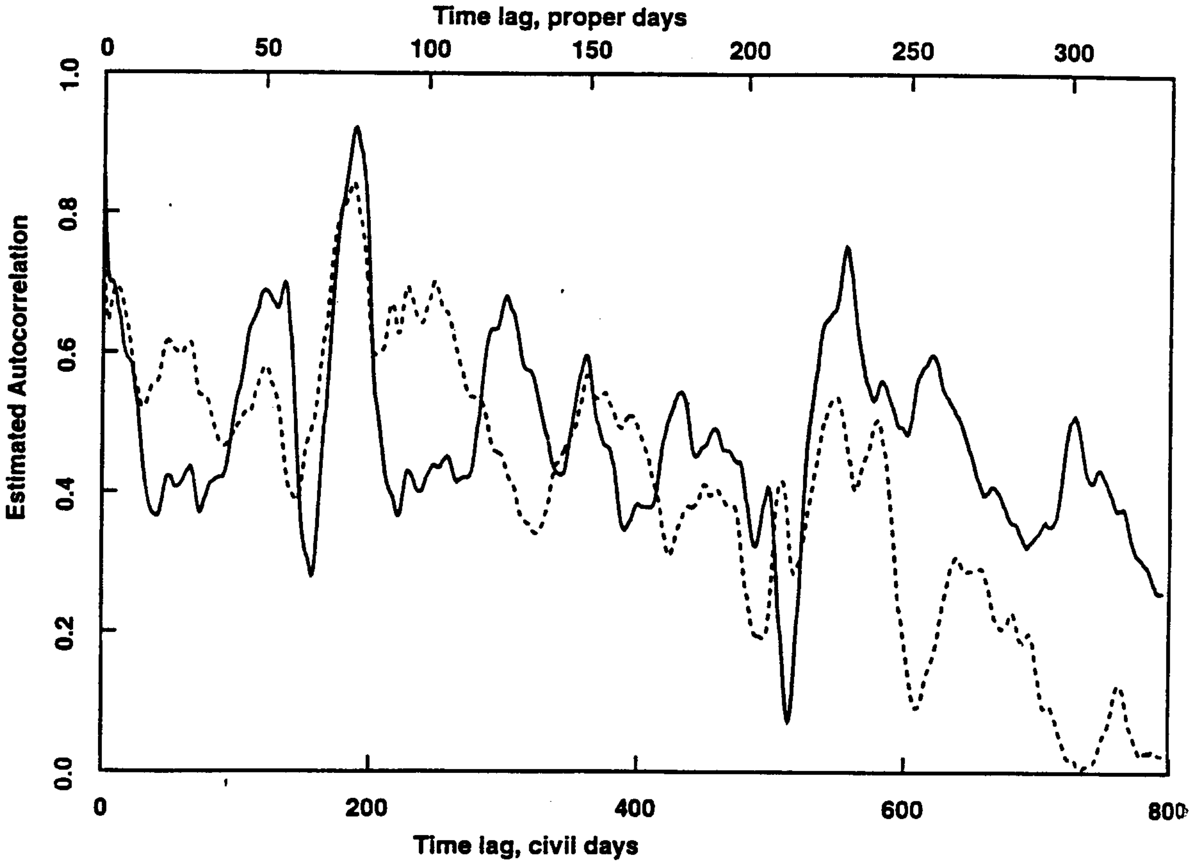

Figure 2. Estimated autocovariance of the A (dashed) and B (solid) light curves. Cross terms are binned at one day resolution and the result smoothed with a taper having an 11 day total extent. Notice the coincidence on the 187 day peaks, and the broad extra peak in the B curve between 100 and 140 days. Subtracting the two curves gives a crudely sinusoidal pattern with a period of 3.4 years.

astronomical sources are unobservable for the season of the year (summer) when the sun is close, and the net result is that our 15-year data record is only 15% complete. Nevertheless, with 850 nights of data presently accumulated, the quasar's brightness fluctuations are reasonably sampled on all time scales.

We display the observed brightness record in Figure 1, where the brightness of each image component is shown as a function of calendar date. The brightness units are magnitudes, an astronomical logarithmic brightness unit where 0.01 mag is a 1% brightness change. A typical observational error is 0.01 mag, and the total range of brightness change observed over the 15 years is about 50%. A rug plot at the bottom of the plot shows the dates when observations were made. Data were interpolated by a weighted least squares fit to Slepian sequences. The fitting interval has been stepped in time, and the fits on the overlapping intervals averaged.

3. THE DATA DON'T AGREE: MICROLENSING

It is immediately evident from a glance at Fig. 1 that the two data records have large differences, even though they are both the observed brightness record of a single distant quasar. The principal difference is a large slope discrepancy observed during the 1980's. This was predicted soon after the gravitational lens was discovered, when it was recognized that the gravitational field of an individual sun-like star in the lens galaxy would have sufficient focusing power to cause additional brightness enhancement over that of the combined masses of the billions of stars that constitute the lens galaxy (Young, 1981; Gott, 1981). Indeed, if the image could be resolved with precision one million times higher than presently possible, it would be recognized that the affected quasar image was itself double (or triple). Calculations showed that for reasonable assumptions about the motions of stars in the lens galaxy, ingress of such a microlensing star should last about 15 years, and a 10-year ingress has perhaps been observed.

Sound propagation in the ocean may provide a helpful analogy. If a distant ship's propeller were exactly behind a water temperature discontinuity, sound could arrive at a sonar detector along two paths with slightly different propagation times. If the size of the temperature discontinuity were known, measurement of the time delay would tell the distance of the propeller. A school of fish entering the warmer region would cause the amplitude to diminish.

In the astronomical case, a more detailed analysis of the data record reveals more complications. Whereas it had long been recognized that the lensing galaxy was made of stars having about the mass of the sun, comparison of the two brightnesses reveals a network of shorter cusps, which can be seen as the raggedness of the data records in Figure 1. What at first appears to be noise is in fact a network of sawtooth-shaped bursts which signal the presence of microlensing masses much smaller than the sun. Our microlensing curve is shown as the lower curve in Figure 1. The gravitational theory shows that the responsible objects must have masses around $10^{-5} M_o$, which would be too small for a shining star and in fact corresponds to about the mass of planet earth. We have determined that these small bursts are not intrinsic to the quasar source, because a wavelet analysis of the pattern of bursts does not show their alignment for any value of time delay. While they contribute noise to our time delay determination, they also hint at a large population of invisibly faint planets in the lens galaxy. In our ocean analogy, it is as if we knew about whales but discovered a large population of small schools of small fish.

Further data processing reveals additional discrepancies. In an autocorrelation plot for the two images, Figure 2, we find very different properties for two images of the same quasar. Autocorrelation peaks that occur at the same lag have different amplitudes in the two quasar images, and many correlation peaks are not at all common to the two images. And why should there be any autocorrelation peaks at all?

We believe that these autocorrelation peaks, with lags of order 100 days, originate in multipaths, or internal source reflections. Light from the central black hole and accretion disc is evidently reflected from inner shells intrinsic to the quasar's structure. Some of the outer shells may be shadowed from the central source by inner shells, at least part of the time. The sky of the black hole is evidently cloudy. Some spectropolarimetric observations of other quasars had already hinted of this.

Our view of the complex source structure is evidently further complicated by the effects of microlensing. The strengths of the autocorrelation peaks are different in different subsets of the data, suggesting that microlensing affects not only the central source, but also the reflecting regions, which are microlensed for periods of a few years, as well. Because the source is so far away, there is no hope of seeing such reflecting structures directly, and so it is remarkable that gravitational lensing apparently allows us to image them with a gravitational telescope that scans across the source structure on time scales of a few years.

Thus far we have referred to the observed quasar brightness fluctuations as the sum of random fueling-based luminosity variations, modified by microlensing when the beams pass through the lens galaxy. We also find a weak pattern of sinusoidal fluctuations having amplitudes of 1/2 % and periods of several days, and high Q. These are probably the gravity-mode oscillations of the quasar's accretion disc (Nowak and Wagoner, 1993). Because several frequencies are found, this exciting development offers the long-term prospect of determining the shape and state of rotation of the black hole.

SO WHAT'S THE TIME DELAY?

In spite of the complications posed by the reflections and the microlensing noise, we have determined the astronomical time delay to be 405 +/- 10 days. When this is combined with other information about the properties of the gravitational field of the lens mass, we conclude that the Hubble expansion parameter is 65 km/sec/Megaparsec, with a corresponding age of 15 billion years. While this value is in basic agreement with other determinations based upon kinds of stars recognizable in the nearest several thousand galaxies, ours is the first exploration of the overall volume of the universe, and not subject to local effects. The universe is still a vast unexplored ocean, and we are charting its continents and peering into its cities without leaving home.

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