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Chandra and *XMM-Newton* Results on the Hubble Constant from Gravitational Lensing

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Abstract

We report the first detection of time-delayed flares in single X-ray observations of the gravitationally lensed quasar PG 1115+080 performed with the *Chandra* and *XMM-Newton* observatories. By combining our observed short time-delay between images A1 and A2 of PG 1115+080 of $\Delta t_{A1A2} = 0.149 \pm 0.006$ days with recent constraints on the mass fraction and slope of the dark matter component of the lensing galaxy (Treu & Koopmans 2002) we are able to narrow the allowable set of lens models for PG 1115+080 and thus obtain a tighter limit on the Hubble constant via the lensing method of $H_0 = 67^{+13}_{-8} \pm 3$ km s^{-1} Mpc^{-1} (random + systematic errors).

1.1 Introduction

The importance of Hubble's constant, H_0, has stimulated the development of a variety of methods for obtaining absolute distances to objects based on their observed redshifts. The accuracy of many of these methods is, however, limited by the reliability of using "standard candles" to establish an absolute distance given a redshift. One of the recent major attempts to measure the cosmic expansion rate is the HST Key Project on the Extragalactic Distance Scale (HSTKP), which finds $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} (Freedman et al. 2001).

To circumvent the cosmic distance ladder approach several methods have recently been developed. In particular, three techniques that do not make use of a distance ladder approach are :(a) a method based on inferring distances to SNeII (Schmidt et al., 1992), (b) the Sunyaev-Zel'dovitch effect and, (c) the gravitational lensing method. The gravitational lensing method was first introduced by Refsdal (1964a,1964b) and provides a means of determining a global value for the Hubble constant based on the measurement of the light travel delay between different images of a gravitationally lensed system (time-delay). Together with a model that describes the gravitational potential of the lens, the time-delay defines the geometrical dimensions of the lens system and may, therefore, lead to the determination of the Hubble constant. One may ask the obvious question; Why measure H_0 when the HST Key project has already measured it accurately? We first point out that the value for H_0 obtained via lensing represents a global value of the expansion rate of our Universe compared to the local value obtained from traditional distance scale methods. In principle local and global measurements of H_0 should be viewed as complementary and may not result in the same value; the local value of the expansion rate of our Universe may differ from an average global one (Koopmans et al. 2001). Second, the lensing method is independent from the HSTKP method and is insensitive to systematic errors of the distance ladder approach, such as, parallax errors, metallicity effects, and local bulk flows. The accuracy of the estimated value of H_0 obtained via Refsdals' method will only improve with time as more accurate time-delays become available and as the number of GL systems with measured time-delays increase. At present over 60 gravitational lens systems have been discovered in the optical and/or radio bands. Ongoing surveys such as the Sloan Digital Sky Survey are expected to uncover many new GL systems. Collectively, such systems will provide tighter constrains on the Hubble constant and other cosmological parameters. Time-delays have been measured in only 9 GL systems with accuracies of about $\sim$ 10%. In particular the most recent time-delay measurements for the lensed quasars Q0957+561, PG 1115+080, B0218+357, HE1104-1805, Q1608+656, PKS1830-211, B1600+434, RX J0911.4+0551, SBS 1520+530, and Q2237+ 0305 yield time-delays of $\Delta\tau_{AB}$ = 417 $\pm$ 3 days(Kundic et al. 1997), $\Delta\tau_{BC}$ = 23.7 $\pm$ 3.4 days(Schechter et al. 1997, Barkana et al. 1997), $\Delta\tau_{AB}$ = 10.5 $\pm$ 0.4 days(Biggs et al. 1999), $\Delta\tau_{BA}$ = 0.73 years(Wisotzki et al. 1998), $\Delta\tau_{AC}$ = 31.5 days(Fassnacht et al. 2000,2002), $\Delta\tau_{AB}$ = 26 $\pm$ 5 days(Lovell et al. 1998), $\Delta\tau_{AB}$ = 51 $\pm$ 4 days (Burud et al. 2000), $\Delta\tau_{AB}$ = 146 $\pm$ 8 days (Hjorth et al. 2002), $\Delta\tau_{AB}$ = 130 $\pm$ 3 days (Burud et al. 2002) and $\Delta\tau_{AB}$ = $2.7^{+0.5}_{-0.9}$ hours (Dai et al. 2003), respectively. The main difficulty in measuring time-delays is that the brightness of each image has to be carefully monitored over several periods of the time-delay and the quasar has to show sufficient variability over time scales smaller than the time-delay. The modest variability of quasars in the optical and radio bands has made it extremely difficult to place accurate constraints on GL time-delays, especially for short time-delays of the order of hours to days. X-ray observations of several GL quasars, on the other hand, show strong variability over time scales of hours to days. Motivated by the detection of a rapid flare in a *Chandra* observation of RX J0911.4+0551, we recently described a method of efficiently measuring accurate short time-delays within single X-ray observations (Chartas et al. 2001). Here we present measurements of the short time-delay in the GL system PG 1115+080 performed with the *Chandra* and *XMM-Newton* observatories. Our measured short time-delay in PG 1115+080 is of particular interest since there has been considerable attention placed on several simple GL systems, such as PG 1115+080, with available accurate long time-delay measurements. Several recent publications (e.g., Kochanek 2002, 2004) conclude that isothermal lens models for these GL systems yield H_0 values in the 40 – 60 km s^{-1} Mpc^{-1} range, whereas, constant M/L ratio models yield H_0 values in the 60 – 80 km s^{-1} Mpc^{-1} range.

1.2 Short Time-Delay Measurements in PG 1115+080

PG 1115+080 was observed with *Chandra* on June 2 and Nov 3 2000 for 26.8ks and 10ks respectively, and was observed with *XMM-Newton* on Nov 25 2001 for 62.6ks. The Lucy-Richardson deconvolved image of the 10ks *Chandra* observation of PG 1115+080 is shown in Figure **??**. The *Chandra* X-ray light-curves of PG 1115+080 are found to be variable over timescales of $\sim$ 1000s. The strength of the variability is a function of the selected energy band as shown in Figure **??**. The Kolmogorov-Smirnov (K-S) test was used as a guide to identify the energy selection band. One possible explanation of the energy dependence of the variability is that the short timescale variations in the X-ray light curve are due to flares on the accretion disk. These flares may have a different spectral shape compared to the continuum X-ray emission resulting in the energy dependence of the variability. The individual light curves of images A1 and A2 in the 2 –3.5 keV band are shown in Figure **??**.

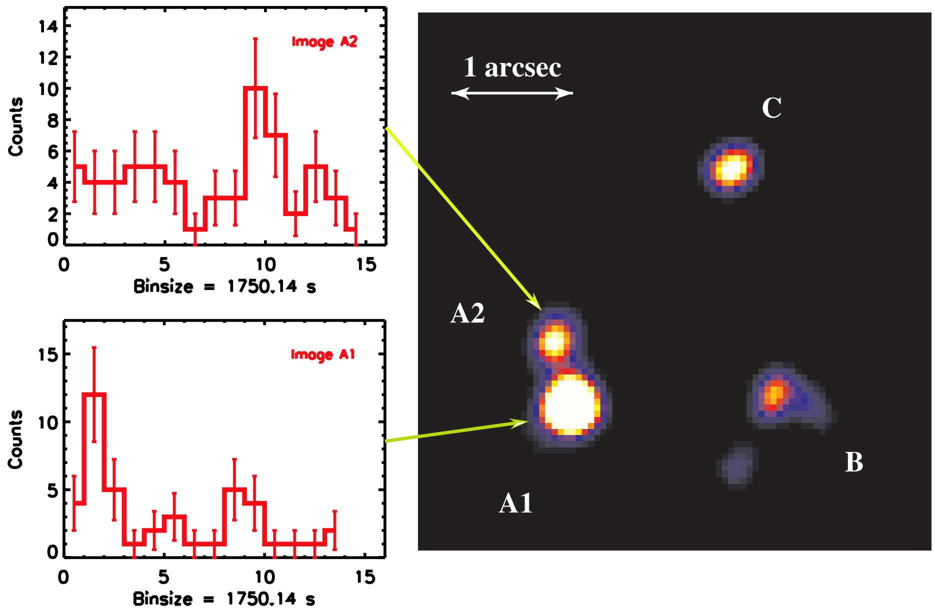

Fig. 1.1. Top left panel: *Chandra* light curve of image A2 of PG 1115+080, Lower left panel: *Chandra* light curve of image A1 of PG 1115+080. Both light curves include X-ray events in the 2–3.5 keV band. Right panel: Lucy-Richardson deconvolved image (0.2 – 8 keV band) of the 10ks *Chandra* observation of PG 1115+080

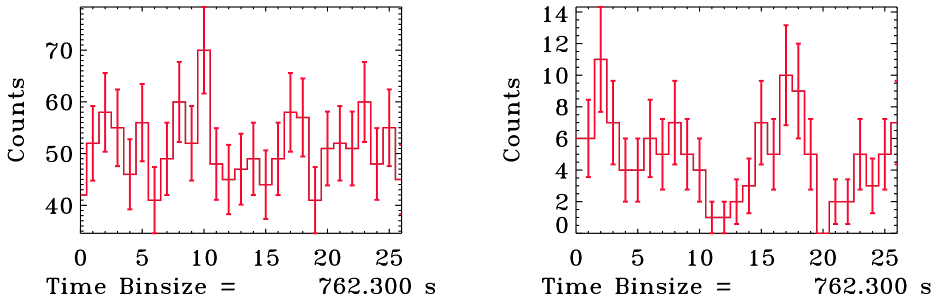

Fig. 1.2. The left and right panels show the combined *Chandra* light-curves of images A1 and A2 of PG 1115+080 in the 0.4 – 7 keV and 2 – 3 keV bands, respectively

We performed a cross correlation of the X-ray light-curves to estimate the time-delay and ran Monte-Carlo simulations to evaluate the significance of the correlation. We find a time-delay between the close images A1 and A2 (0.48″ apart) of $\Delta t_{A1A2} = 0.16 \pm 0.02$ days with

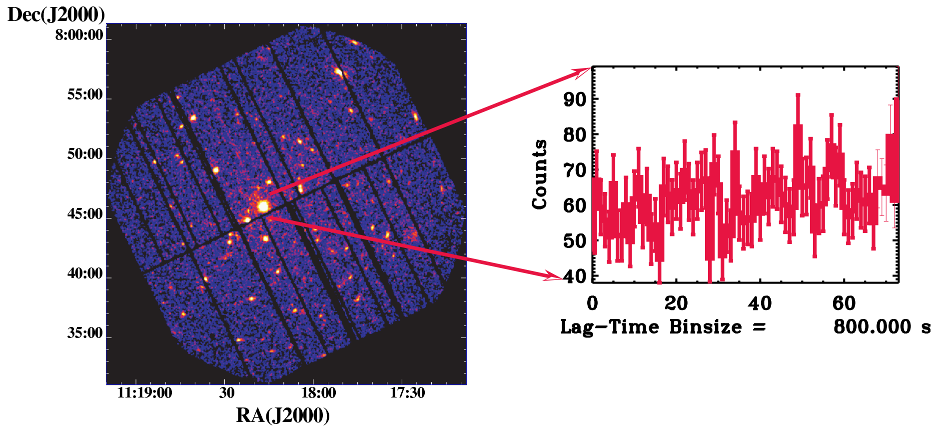

Fig. 1.3. Left panel: *XMM-Newton* image (taken with the PN instrument) of the PG 1115+080 field, Right panel: Light Curve of PG 1115+080 in the 0.6 - 1.7 keV band taken with the PN instrument onboard *XMM-Newton*

image A1 leading. The amplitude of the cross correlation signal is 0.7 and the probability of obtaining such a value by chance is less than 1%.

An independent measurement of the time-delay between images A1 and A2 of PG 1115+080 was provided by the recent *XMM-Newton* observation of this GL system. The *XMM-Newton* image of the PG1115+080 field and the combined light curve of all images of PG 1115+080 in the 0.6 - 1.7 keV band are shown in Figure **??**. The spatial resolution of *XMM-Newton* of $\sim 10''$ does not allow us to resolve the light curves of the individual images of PG 1115+080. The method used for extracting a short time-delay from the *XMM-Newton* observation of PG 1115+080 differs from the approach used in the *Chandra* observations of this system. The method is summarized as follows. We first obtain a background subtracted light-curve of the combined images A1,A2, B and C of the *XMM-Newton* observation of PG 1115+080. Auto correlations (AC) of the X-ray light-curves were performed over a range of energy bands to determine AC lag-times. We created a histogram of the time-delays that correspond to the maximum values of the AC coefficients. This histogram is filtered for light-curves that meet a set of criteria. In our case the filtering criteria were (a) the K-S chance probability of variability of a light-curve be less than 0.1 and (b) the probability of obtaining the maximum AC coefficient by chance in a light-curve be less than 0.1. Monte-Carlo simulations were performed to evaluate the errors in the time-delay. We also investigated the sensitivity of the derived time-delay to the selected binsize of the light-curve. This error has been included in the error analysis of the time-delay. In Figure **??** we show the histogram of the AC lag times corresponding to the maxima of the AC coefficients with K-S chance probabilities of variability in each light-curve of less than 0.1 and Monte-Carlo chance probabilities of obtaining each AC coefficient of less than 0.1. We find that a time-delay between images A1 and A2 of $\Delta t_{A1A2} = 0.149 \pm 0.006$ days.

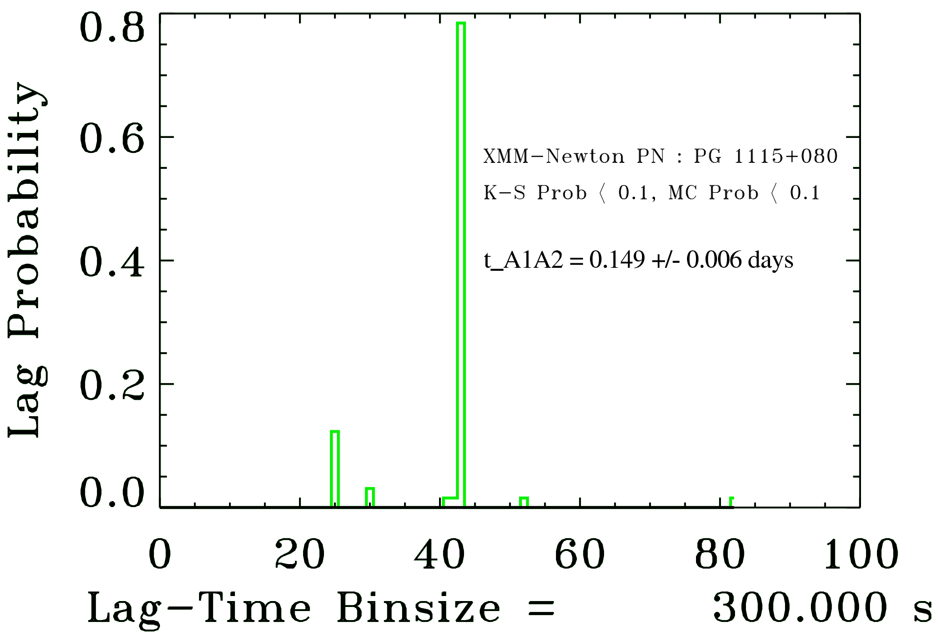

Fig. 1.4. The histogram of the auto correlation (AC) lag times of the *XMM-Newton* light-curves of different X-ray bands of the combined images of PG 1115+080 corresponding to the maxima of the AC coefficients with K-S chance probabilities of variability in each light-curve of less than 0.1 and Monte-Carlo chance probabilities of obtaining each AC coefficient of less than 0.1.

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1.3 Discussion

The values for H_0 derived from present measurements of long time-delays depend strongly on the assumed mass profiles of the lenses (e.g., Impey et al. 1998, Kochanek 2002, 2004). Isothermal lens models predict $H_0 \sim$ 40–50 km s^{-1} Mpc^{-1}, whereas constant M/L ratio models predict $H_0 \sim$ 60–80 km s^{-1} Mpc^{-1}. We investigated whether the accurate X-ray measurement of the time-delay Δt_{A1A2} in PG1115+080 can discriminate between mass models. We used KeetonÕs gravitational lensing software `gravlens` 1.04 to produce a range of lens models, fitted these models to the observables and predicted the time-delays for each model. We essentially reproduced the models described in Impey et al. (1998) and Treu & Koopmans (2002). In Table **??** we show the predicted time-delays and resulting values for the Hubble constant for three different lens models.

The first model consists of a singular isothermal ellipsoid (SIE) model to represent the principal lensing galaxy and a singular isothermal sphere model to represent the galaxy group that is known to contribute to the lensing of this system. For the second model we assume a de Vaucouleurs profile for the main galaxy and a SIS model for the galaxy group. The de Vaucouleurs profile approximates a constant mass-to-light lens model for the main galaxy. Finally, for the third model we assume a Pseudo Jaffe model for the luminous component of the main galaxy, a cuspy model for the dark matter component of the main

Table 1.1. *Predicted Time-Delays Between Images A1 and A2 of PG 1115+080 and Resulting Values of the Hubble constant.*

Lens Model	A1	A2	B	C	δt_{A1A2}	h
SIE + SIS	14.0640	14.2265	25.	0	0.162	0.4528
de Vaucouleurs + SIS	14.0806	14.2546	25.	0	0.174	0.6809
JF + Cusp + SIS	14.1597	14.3291	25.	0	0.169	0.5962

NOTE-
SIE is a singular isothermal ellipsoid model, SIS is a singular isothermal sphere potential used to model the nearby group of galaxies that contributes to the lensing of PG 1115+080, de Vaucouleurs is a constant mass-to-light lens model, JF is a Pseudo Jaffe model for the luminous component of the lensing galaxy, Cusp is a cuspy model for the dark matter component of the lensing galaxy. The third model in Table **??** is based on lens model of Treu & Koopmans (2002) that includes both lensing constraints (image positions, main lens position and flux ratio) and kinematic constraints (mass fraction and slope of dark matter density profile of lens). All time-delays are in units of days and computed with respect to image C. The time-delay between images B and C for these simulations has been set to the estimated time-delay of 25 days by Barkana et al. (1997) based on the observations of Schechter et al. (1997). $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$

galaxy, and a SIS model for the galaxy group. The third model is based on the lens model of Treu & Koopmans (2002) that includes both lensing constraints (image positions, main lens position and flux ratio) and kinematic constraints (mass fraction and slope of dark matter density profile of lens). The estimates in Table **??** assume a time-delay between images B and C of 25 days. We note that all models predict time-delays between images A1 and A2 that are larger than the X-ray measured value. Our measured time-delay between images A1 and A2 combined with the third model of Table **??** imply a time-delay between images B and C of about 22 days which is consistent with the Schechter et al. (1997) value of Δt_{BC} = 23.7 ± 3.4 days (1σ errors) but only marginally consistent at the 95% confidence level with the Barkana et al. (1997) value of $\Delta t_{BC} = 25.0^{+3.3}_{-3.8}$ days (95% confidence levels). If we scale the third model that contains the additional constraints on the mass fraction and slope of the dark matter component from Treu & Koopmans (2002) to have Δt_{A1A2} = 0.149 hours we obtain a Hubble constant of $H_0 = 67^{+13}_{-8} \pm 3$ km s^{-1} Mpc^{-1} (random + systematic errors).

1.4 Conclusions

We have presented a measurement of a short time-delay from X-ray observations of PG 1115+080. Our analysis of the light-curve of the *XMM-Newton* observation of PG 1115+080 constrains the time-delay between images A1 and A2 to be Δt_{A1A2} = 0.149 ± 0.006 days, consistent with an earlier value obtained from a *Chandra* observation of PG 1115+080. Combining the X-ray time-delay measurement and the recent lens model of PG 1115+080 (Treu & Koopmans 2002) results in a value of $H_0 = 67^{+13}_{-8} \pm 3$ km s^{-1} Mpc^{-1} (random + systematic errors).

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