A New Estimate of Hubble's Constant from the Gravitational Lens PKS 1830-211

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The Einstein ring gravitational lens PKS 1830-211 consists of two bright, milliarcsecond-scale radio components separated by 1 arcsec and connected by a fainter ring of radio emission (Rao and Subrahmanyan 1988; Jauncey *et al.* 1991). The galaxy believed to be primarily responsible for this morphology has a redshift of z = 0.89 (Wiklind and Combes 1996), and a preliminary estimate of $H_\circ$ has been made by Lovell *et al.* (1998) using a previously published model for the system by Nair *et al.* (1993) and a new redshift for the background radio source. However, a second intervening galaxy at z = 0.19 is also known to exist from radio absorption line observations (Lovell *et al.* 1996). In this paper we consider the possible effects of this lower redshift galaxy on estimates of $H_\circ$.

We assume a standard cold dark matter cosmology: $\Omega = 1$, $\Lambda = 0$, $H_\circ = 100\,h$ km s^{-1} Mpc^{-1}. Let D_{OL}, D_{OS} and D_{LS} be the angular diameter distances between the observer and the lens, the observer and the background source, and between the lensing galaxy and the background source, respectively. The angular diameter distance is given by

$$D = \frac{c}{H_\circ q_\circ^2 (1+z)^2}\left(q_\circ z + (q_\circ - 1)\left[(1+2q_\circ z)^{1/2} - 1\right]\right)$$

$$= \frac{2\,c}{H_\circ (1+z)^2}\left(1 + z - (1+z)^{1/2}\right)$$

for $q_\circ = 1/2$. Using $z = 0.89$ for the lensing galaxy, we get $D_{OL} = 865\ h^{-1}$ Mpc. For D_{OS} and D_{LS} we use the recently-published redshift of 2.5 for the background radio source (Courbin, *et al.* 1998; also reported by Lovell *et al.* 1998). This gives $D_{OS} = 798\ h^{-1}$ and $D_{LS} = 331\ h^{-1}$. The values of D_{LS} were computed from the formula

$$D_{LS} = \frac{2\ c}{\mathrm{H_o}} \frac{[(1+z_L)^{1/2}(1+z_S)\ -\ (1+z_L)(1+z_S)^{1/2}]}{(1+z_L)\ (1+z_S)^2}$$

The mass of the $z = 0.89$ lensing galaxy can be estimated from the Einstein ring radius θ_E:

$$M_L = \frac{\theta_E^2\ c^2}{4\ \mathrm{G}} \frac{D_{OL}\ D_{OS}}{D_{LS}}$$

For $\theta_E = 0.5$ arcsec this gives $6.4 \times 10^{10}\ h^{-1}\ \mathrm{M}_\odot$ for the lens mass within the Einstein ring (thus it is a lower limit to the total mass of the lensing galaxy).

For a point mass lens, the time delay expected between two images separated by $2\theta_E$ is given by (Lehar 1991):

$$\Delta\tau = -(1+z_L)\frac{4GM}{c^3}\left[\frac{\theta_s\sqrt{\theta_s^2+4\theta_E^2}}{2\theta_E^2} + \ln\left(\frac{\theta_s+\sqrt{\theta_s^2+\theta_E^2}}{|\theta_s-\sqrt{\theta_s^2+\theta_E^2}|}\right)\right]$$

where θ_s is the angle between the center of the lensing galaxy and the true (undeflected) position of the background source. This angle can only be determined from a detailed model of the lens geometry. The lens model derived by Nair, Narasimha, and

Rao (1993) predicts that $\theta_s = 0.144$ arcsecond. Combining this with our observed values for θ_E and z_L allows us to reduce the above equation to

$$\Delta\tau \; = \; 2.2 \times 10^{-5} \; (\frac{M}{M_\odot}) \; \text{seconds.}$$

Using our lens mass estimate above we get a time delay of $1.41 \times 10^6 \; h^{-1}$ seconds or $16.4 \; h^{-1}$ days. Equating this with the observed 26^{+4}_{-5} day value for the time delay (Lovell *et al.* 1998) gives $0.54 \leq h \leq 0.78$, with a most probable value of $h = 0.63$.

A point source model is unlikely to be a very good approximation for the lensing galaxy. To see how important this simplifying assumption is, we can compare the results above with those derived from the explicit Nair, Narasimha, and Rao lens model. Their model consists of an oblate spheroid with a power law mass density distribution and a nuclear core containing about 1% of the total galaxy mass. The total mass of the lensing galaxy in their model is $1.17 \times 10^8 \; (D_{OL} D_{OS}/D_{LS})$ $M_\odot$. As expected, these values are higher (by a factor of 3.9) than the values derived above for the mass within the Einstein ring. The Nair, Narasimha, and Rao model predicts a time delay between the NE and SW VLBI components of:

$$\Delta\tau = \; -8.15 \times 10^{-3} \left(\frac{D_{OL} \; D_{OS}}{D_{LS}} \right) \; \text{days}$$

With $\Delta\tau = -26$ days we get $h = 65$, in good agreement with the value derived using a point source lens model. However, both the Nair model and the point source model fail to take the lower redshift galaxy into account.

To estimate the effect of the z = 0.19 galaxy on these results, we need to have some idea of how far from the lens axis it is. The neutral hydrogen absorption detected by Lovell *et al.* (1996) is much stronger along the line of sight to the NE component than to the SW component, suggesting that the z = 0.19 galaxy is much closer to the position of the NE component on the sky. Such an alignment could also explain the more elongated and complex VLBI morphology of the NE radio component compared with the SW component. NICMOS images obtained by the CASTLES group (C.S. Kochanek, *et al.* 1998) are shown in figures 1-3. Note the region of yellow between the galactic M star and the NE lens component in the H image. This may be emission from the lower redshift intervening galaxy - the emission appears to be extended, and is in a plausible location with respect to the two compact lensed images. An additional hint of emission from this location may be visible as a bright (white) region within the NE component Airy ring in the I image (although the asymmetries in the Airy pattern makes this uncertain), and in the extension of yellow to the east of the region between the M star and NE component in both the I and K images.

If we **assume** that the z = 0.19 galaxy is located in the region between the M star and NE component, the angular offset between the galaxy and the NE and SW lensed components are approximately 0.3 and 1.2 arcsec, respectively. At the distance of the galaxy 1 arcsec $\approx$ 2.1 kpc, so these correspond to linear offsets of 0.6 and 2.5 kpc.

The additional time delay along a path from a source S to an observer O and passing a distance R from a lens L of mass M is given by (Misner, Thorne, & Wheeler 1973):

$$\Delta\tau = M \ln\left[\frac{(D_{OL} + \sqrt{{D_{OL}}^2 + R^2})(D_{LS} + \sqrt{{D_{LS}}^2 + R^2})}{R^2}\right].$$

The difference between the NE and SW component time delays caused by the z = 0.19 galaxy is $1.6(M/10^{10}M_\odot)$ days, where M is the (unknown) mass of the z = 0.19 galaxy. If we assume a plausible mass of 3×10^{10} $M_\odot$ we get a differential delay of 4.8 days, with the NE component line of sight experiencing the larger additional delay. Since the NE component leads the SW component in radio variability, the effect of this additional delay is to increase the differential delay which should be used in conjunction with the Nair *et al.* (1993) lens model. The effect of a 4.8 day increase in differential delay is to decrease the resulting range of h:

$$0.47 \leq h \leq 0.63$$

with a most probable value for the Hubble constant of $\mathbf{H_o = 53\ km\ s^{-1}\ Mpc^{-1}}$. Note, however, that a range of 10^{10} to 10^{11} $M_\odot$ for the mass of the z = 0.19 galaxy results in a correction to the measured time delay of 1.6 to 16 days; that is, from nearly negligible to very large. Consequently there is a significant additional source of systematic error which should be added to the range of h values determined from the uncertainly in measuring the time delay. Future observations will be needed to constrain the mass of the z = 0.19 galaxy and allow an accurate two-lens model for this system to be developed. Estimates of the Hubble constant determined from single-lens models for this system must be considered upper limits.

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