Observing the Cosmic Horseshoe

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25/03/2015

Abstract
The Cosmic Horseshoe is a gravitational lens system in the constellation Leo and was first discovered by Belokurov et al. (2007). This system can be used to determine the amount of dark matter in the lens galaxy by determining the enclosed mass and the visible mass of the system and then calculating the difference. We want to use the Wide Field Camera on the Isaac Newton Telescope for this purpose. Photometric data from three different filters is required; specifically the Sloan g, r and i filters. We propose to observe this system for two hours on the 5th of May 2015 in order to obtain detailed photometric data and to probe the mass and the light profile of the lens galaxy.

I. Scientific Justification

Dark matter may be one of the greatest mysteries in current research. Gravitational lensing systems provide an excellent cosmological laboratory for understanding the nature of gravity, including the influence of dark matter. General relativity predicts the existence of gravitational lenses in space. These occur when massive objects are located in front of background objects, like galaxies. The gravitational field of the foreground object warps the space-time environment, which causes the light of background objects to be lensed. Few gravitational lensing systems have been found and most of them are partial rings.

Belokurov et al. (2007) reported the discovery of an almost complete Einstein ring around a giant luminous red galaxy (figure 1) in Sloan Digital Sky Survey Data Release 5 [1]. The ring consists of a star-forming galaxy at z = 2.379 for H_0 = 70 km/s/Mpc. The foreground object (LRG 3-757, redshift z = 0.445) belongs to a rare class of galaxies, called luminous red galaxies, and is found to be extremely massive ($\sim 5.4 \cdot 10^{12}$ $M_\odot$).

Our goal is to determine the mass of the dark matter within this Einstein ring with a reasonable error margin. For this purpose we want to use the Isaac Newton Telescope (INT) and its on-board Wide Field Camera (WFC). Photometric data is required to precisely determine the radius of the Einstein ring and to make an intensity profile of the foreground galaxy. With this radius we can then determine the enclosed mass within the ring. With photometric data in three different filters (g, r, i) we can determine the mass of the visible matter inside the ring. Evaluation of the difference in these two masses yields an estimate of the mass of the dark matter in this lens system.

If we approximate that source and lens are perfectly aligned and that the universe is flat ($\Omega_k = 0$), we can use the following formula to calculate the enclosed mass [2]:

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} = \sqrt{\frac{4GM}{c^2}\frac{D_s(1+z_s) - D_L(1+z_L)}{(1+z_S)D_L D_S}} \,,$$

with θ_E the angular radius of the ring (in radians), G the gravitational constant, M the mass within the ring, D_{LS} the angular diameter distance between the lens and the source, D_S the angular diameter distance to the source, D_L the angular diameter distance to the lens, z_S the redshift of the source, z_L the redshift of the lens and c the speed of light. Since we don't have a spectrograph to determine the distances D_L and D_S and the redshifts z_L and z_S, we look up these values from literature. The mass of the foreground galaxy will be calculated numerically by using the package FAST[1]. The procedures described above should allow us to determine the presence of dark matter in this system.

II. Technical Justification

The observation days take place from the 2nd to the 6th of May 2015. The program Staralt[2] tells us that the object is clearly visible at high altitude during all of the four days of observation (figure 2) and thus making our moment of observation very flexible. However, to obtain the best possible data we need to observe on the night of the 5th of May, since the full moon is then farthest away.
We want to use the three Sloan filters (g, r, i) for our observations. The lensed galaxy is a young galaxy that emits strongly in the lower wavelength regions of the electromagnetic spectrum. The lens galaxy is a giant luminous red galaxy that emits strongly in the red and infrared wavelength regions. Our initial intention was to use a U filter besides the three Sloan filters. Unfortunately, the moon is prominently present during the days of observation, which causes the sky to have a strong influence on our measurements in the lower wavelength filters. Instead of using the U filter, we use the g filter, which will be less affected by the sky. In the beginning of the evening we take a dark field and bias frame. Then we need to perform two measurements in each filter:

- Flat field
- Image

We use the magnitudes in the SDSS catalogue[3] (table 1) to make an estimate for the exposure times needed. The exposure times can be calculated with the tool Exposure Time Calculator [4]. To acquire decent photometric data we need a signal-to-noise ratio of around 50 (figure 3). If we take into account the effect of the full moon on the sky during our observations, the suboptimal weather conditions that may occur and the fact that the object is relatively faint, we conclude that a total time of 20 minutes is needed in each filter: 10 minutes for the image, 2 minutes for the sky, 5 minutes for the rest and 3 minutes for technical purposes. We propose for an observation time of two hours in the night of the 5th of May.

Filter	g	r	i
Apparent magnitude	20.75	18.93	18.15

Table 1: *The magnitudes of the Cosmic Horseshoe in the three Sloan filters as taken from the SDSS archive.*

[1] `http://astro.berkeley.edu/~mariska/FAST.html`
[2] `http://catserver.ing.iac.es/staralt`
[3] `http://skyserver.sdss.org/dr12/en/tools/explore/Summary.aspx?id=1237668293376278947`
[4] `http://catserver.ing.iac.es/signal/`

APPENDIX

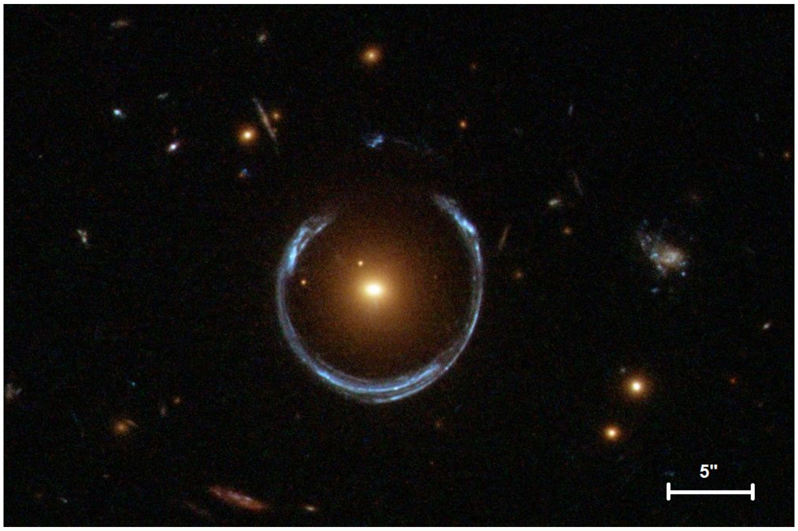

Figure 1: *Image of the Cosmic Horseshoe Einstein ring (Ra = 11h 48m 33.47s, Dec = 19° 29' 40.09"), taken by the Hubble Space Telescope. North is 92.1° right of vertical.*

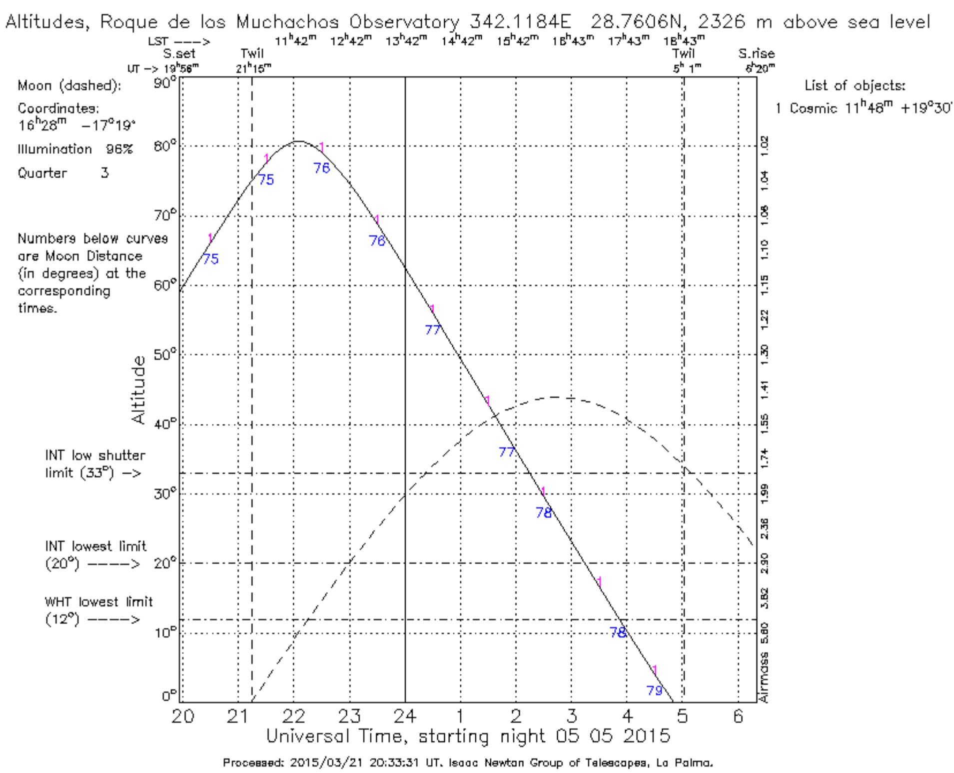

Figure 2: *Staralt image of the Cosmic Horseshoe on May 5th 2015.*

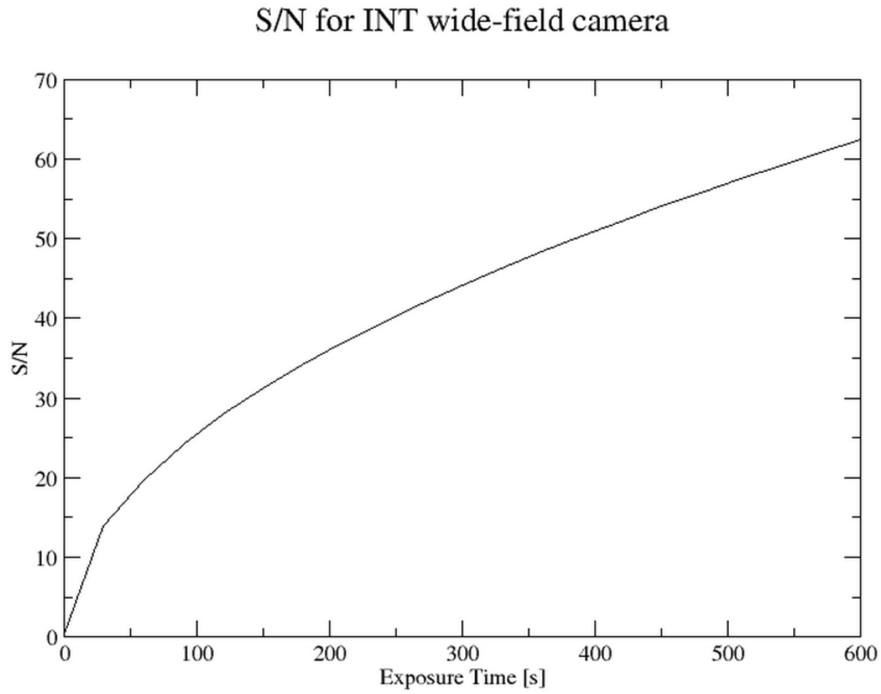

Figure 3: *Predicted signal-to-noise ratio in a B filter for the INT wide-field camera. This graph should be a lower limit, since the object emits stronger in the higher wavelength regions.*

References

[1] Belokurov, V. et al. (2007), *The Cosmic Horseshoe: Discovery of an Einstein Ring around a Giant Luminous Red Galaxy*, The Astrophysical Journal Letters, vol. 671 (1), L9.

[2] Hogg, D.W. (1999), *Distance measures in cosmology*, arXiv:astro-ph/9905116, equation 19.