GRAVITATIONAL LENSES AS STANDARD RULERS IN COSMOLOGY*

Marek Biesiada, Aleksandra Piórkowska

Institute of Physics, Department of Astrophysics and Cosmology
University of Silesia
Uniwersytecka 4, 40-007 Katowice, Poland

Beata Malec

Copernicus Center for Interdisciplinary Studies
Gronostajowa 3, 30-387 Kraków, Poland

(Received October 6, 2011)

The accelerating expansion of the Universe is a great challenge for both physics and cosmology. From the observational point of view, it is crucial to have various methods to assess cosmic expansion history, which can be alternative to standard candles (SNIa in cosmological context). Strongly gravitationally lensed systems create such a new opportunity by combining stellar kinematics with lensing geometry. Using strong gravitational lenses as probes of cosmic expansion is becoming attractive in light of ongoing surveys like SLACS based on different protocols than older searches focused on potential sources. In this approach, pursued recently by the authors, strongly lensed systems with known central velocity dispersions act as "standard rulers" — Einstein radius being standardized by stellar kinematics.

DOI:10.5506/APhysPolB.42.2287
PACS numbers: 98.62.Sb, 98.80.Es

1. Introduction

The accelerating expansion of the Universe is one of the most important issues in modern science, and indeed a great challenge to both physics and cosmology. It appeared at the end of the XX century as a result of the advances in accuracy of extragalactic distance measurements. Discovery of this phenomenon on the Hubble diagrams obtained from the SNIa surveys [1] in combination with independent estimates of the amount of baryons and cold

* Presented by M. Biesiada at the XXXV International Conference of Theoretical Physics "Matter to the Deepest", Ustroń, Poland, September 12–18, 2011.

dark matter [2] led us to believe that most of the energy in the Universe exists in the form of mysterious dark energy. Whether dark energy is attributable to a real material component still remains to be established. The new physics of dark energy may lie in the nature of gravity itself, the quantum vacuum, or extra dimensions. Whatever the true solution of accelerating expansion is, surely any observational method providing alternative way of measuring cosmic distances will be important. The potential of constraining dark energy models with SNIa data alone, even though ever increasing, would not be sufficient if taken alone in separation form the other approaches. Therefore, every alternative method of probing the cosmic expansion history is desired. In particular, along with standard candles (like SNIa), one should consider standard rulers as well.

In this paper, we point out that strong gravitationally lensed systems can serve as a new class of standard rulers for cosmology.

2. Distance measures

The main paradigm of modern cosmology is that geometry of the Universe can be described as one of three possible Friedman–Robertson–Walker (FRW) solutions to the Einstein equations representing homogeneous and isotropic spacetime. Currently there exists strong evidence, coming form independent and precise experiments, that the Universe is spatially flat. For example, a combined analysis of cosmic microwave background, baryon acoustic oscillations (BAO) and supernova data [3] gives $\Omega_{\rm tot} = 1.0050^{+0.0060}_{-0.0061}$. The only gravitational degree of freedom, in the FRW cosmology, is the scale factor $a(t)$ depending on cosmic time t and responsible for temporal changes of spatial length-scales (known as cosmic expansion). Unfortunately it is not directly observable. However, there is a unique correspondence between $a(t)$ and redshift z which is an observable quantity. Namely, $a(z) = (1+z)^{-1}$. The Einstein equations in FRW model allows for a very convenient parametrization of the expansion rate $H(t) = H_0^2 h(t)^2$

$$H(t)^2 = H_0^2 \left[\Omega_m a(t)^{-3} + \Omega_r a(t)^{-4} + \Omega_X a(t)^{-3(1+w_X)} + \Omega_k a(t)^{-2} \right] , \quad (1)$$

where Ω_i, $i \in \{m, r, X, k\}$ denote present energy density[1] of respective components (matter, radiation, other non-standard barotropic component X *e.g.* for cosmological constant we have $w_\Lambda = -1$ and Ω_Λ is just a constant term). The last term is the so-called curvature term and is zero for the flat model. The present value of cosmic expansion rate is known as the Hubble constant H_0. Thus we see that the expansion rate $H = \frac{\dot{a}}{a}$ is determined by some set of parameters like H_0, Ω_m, Ω_r or Ω_X (if other components X are considered)

[1] As a fraction of critical density.

and the equation of state parameter w_X. We will use a shorthand notation of $\boldsymbol{p}$ for such parameters. Technically speaking, testing cosmological models means to determine parameters $\boldsymbol{p}$ from observable quantities measured on samples of extragalactic objects lying far enough to feel the large-scale geometry of space-time. This specific goal of cosmology is currently called cosmography.

It is quite obvious that one very direct approach could be to test the distance — redshift relation $D(z)$ (called the Hubble diagram when plotted) whenever there is a possibility to determine distances and redshifts independently. However, as a consequence of non-Euclidean geometry assumed, one distinguishes three types of distances in cosmology: the comoving distance, luminosity distance and angular diameter distance. We are not able to measure the comoving distance directly. However, the last two distances are based on clear observational concepts, but in order to use them we should have standard candles and standard rulers, respectively. Standard candles are objects with known luminosity L; we measure the flux F so one can assess the luminosity distance from the well known relation: $L = 4\pi D_{\mathrm{L}}^2 F$. In fact, this relation is the definition of the luminosity distance D_{L}. Similarly, when we have standard rulers, *i.e.* the objects whose size R is *a priori* known, one can assess how distant they are from measuring their angular sizes θ. Then, of course, $R = D_{\mathrm{A}}\theta$. This relation is known from ancient times and serves as a definition of the angular diameter distance D_{A}.

Supernovae Ia are the most important standard candles in cosmology [1]. The reason for this is that they are bright enough to be detected in distant galaxies and those occurring in nearby galaxies can be calibrated by reliable independent distance measurements based on Cepheids or other local distance tracers. Using SNIa we can probe the cosmic expansion up to redshift $z = 1.7$. A new promising class of standard candles detectable up to the redshift of $z = 6$ is offered by gamma ray bursts [4]. Final stages of evolution of NS–NS binary systems, and more specifically the signal which is supposed to be observed in next generation of gravitational wave detectors, theoretically can serve as a new class of standard candles [5]. Now, the point is that standard candles are not exactly "standard" but rather "standardizable". For example, SNIa do not have exactly the same luminosity — some amount of scatter in peak luminosity occurs. It is, however, correlated with the duration of the SN event — intrinsically brighter SNe last longer. Therefore, one can use the so-called stretch factor to produce a standardized lightcurve for each individual event.

Standard rulers are becoming increasingly popular in cosmology. They fall into two classes. First, statistical standard rulers *i.e.* acoustic peaks in the CMBR anisotropy power spectrum and baryon acoustic oscillations seen in galaxy distribution (see [6] for a review). Second class comprises individual standard rulers such as: ultra compact radio sources [7], double-sided radio sources [8] and galaxy clusters for which X-ray data can be combined with Sunyayev–Zel'dovich effect [9]. They also are not quite standard but rather standardizable. What we want to point out here is that strong gravitational lenses offer another class of standardizable rulers.

3. Gravitational lenses

Gravitational lensing of quasars and extragalactic radio sources at high redshifts by foreground galaxies is now well established and has developed into a mature branch of astrophysics in both theoretical and observational dimensions [10, 11]. Modern advances in gravitational lensing as a tool for cosmology are reviewed in [12] upon which general remarks outlined below in this chapter are based.

Imagine the source, observer and some other massive object (the lens) located exactly along a line. From the point of view of traditional optics the source would be obscured by the intervening object. General relativistic phenomenon of light deflection near massive bodies changes this picture: out of all light rays emitted radially some get now focused at the observer. The intervening massive body acts as a lens and a source behind reveals its existence as a luminous ring — the so-called Einstein ring. Even the smallest misalignment of the source, the lens and observer results typically in multiple images whose angular positions and magnification ratios allow reconstructing lensing mass distribution.

The most useful notion in gravitational lensing theory is the Einstein radius $\theta_{\rm E}$. In circular lenses it is the radius of the circle inside which the average projected mass density is equal to critical density $\Sigma_{\rm cr} = c^2 D_{\rm s}/(4\pi G D_{\rm l} D_{\rm ls})$, where $D_{\rm s}$, $D_{\rm l}$ and $D_{\rm ls}$ denote respectively the *angular diameter distance* to the source (at redshift $z_{\rm s}$), the lens (at redshift $z_{\rm l}$) and between the lens and the source. Thus the Einstein radius defines the deflection scale of a given lens.

The lensing is called strong if source position happens to lie within the circle of a radius $\theta_{\rm E}$. In this case multiple images appear. In the opposite case (*i.e.* the light-rays from the source passing by the lens outside its Einstein radius) there are no multiple images. Even in this case, however, the light-ray bundles experience a systematic distortion which changes the shape of the lensed source. This phenomenon is called weak lensing, has its own place in cosmology [11] and is beyond the scope of this paper.

A surprisingly realistic model of the lens potential is that of a singular isothermal sphere (SIS) in which the 3-dimensional mass density has the following profile

$$\rho = \frac{\sigma_{\rm SIS}^2}{2\pi G r^2}\,. \tag{2}$$

The Einstein ring radius for the SIS model is

$$\theta_{\rm E} = 4\pi \frac{D_{\rm ls}}{D_{\rm s}} \frac{\sigma_{\rm SIS}^2}{c^2}\,, \tag{3}$$

where $\sigma_{\rm SIS}$ denotes one-dimensional velocity dispersion of stars in lensing galaxy.

4. Strong lensing systems as standard rulers

The main idea is that the formula for the Einstein radius in a SIS lens (3) depends on the cosmological model through the ratio of (angular-diameter) distances between lens and source and between observer and lens [13]. The angular diameter distance in flat Friedmann–Robertson–Walker cosmology is given by

$$D_A(z;\boldsymbol{p}) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{dz'}{h(z';\boldsymbol{p})}\,. \tag{4}$$

Provided one has reliable knowledge about the lensing system: *i.e.* the Einstein radius $\theta_{\rm E}$ (from image astrometry) and stellar velocity dispersion $\sigma_{\rm SIS}$ (form central velocity dispersion σ_0 obtained from spectroscopy) one can use it to test the background cosmology. This method is independent of the Hubble constant value (which gets canceled in the distance ratio) and is not affected by dust absorption or source evolutionary effects. It depends, however, on the reliability of lens modeling (*e.g.* SIS assumption) and measurements of σ_0. Hopefully, starting with the Lens Structure and Dynamics (LSD) survey and the more recent SLACS survey spectroscopic data for central parts of lens galaxies became available allowing to assess their central velocity dispersions. There is a growing evidence for homologous structure of early type galaxies [14, 15] supporting reliability of SIS assumption. In particular, it was shown there that inside one effective radius massive elliptical galaxies are kinematically indistinguishable from an isothermal ellipsoid (SIE) — a straightforward generalization of the isothermal sphere (SIS).

In the method outlined above, cosmological model enters not through a distance measure directly, but rather through a distance ratio

$$\mathcal{D}^{\rm th}(z_{\rm l}, z_{\rm s};\boldsymbol{p}) = \frac{D_{\rm s}(\boldsymbol{p})}{D_{\rm ls}(\boldsymbol{p})} = \frac{\int_0^{z_{\rm s}} \frac{dz'}{h(z';\boldsymbol{p})}}{\int_{z_{\rm l}}^{z_{\rm s}} \frac{dz'}{h(z';\boldsymbol{p})}} \tag{5}$$

and respective observable counterpart reads

$$\mathcal{D}^{\rm obs} = \frac{4\pi\sigma_0^2}{c^2\theta_{\rm E}}\,.$$

This has certain consequences both advantageous and disadvantageous. The positive side is that the Hubble constant H_0 gets canceled, hence it does not introduce any uncertainty to the results. On the other hand, we have a disadvantage that the power of estimating Ω_m is poor. Putting aside the issue that the observable quantity here is a distance ratio, one can see that strong lenses constitute a class of standard rulers. They could be better called "standardizable" rulers because each lens has intrinsically different Einstein radius, but stellar kinematics, *i.e.* velocity dispersion allows for disentangling the effect of mass from that of distances.

The above method extensively investigated by [16] on simulated data was first used in practice to constrain various cosmological models in [17] where ΛCDM, quintessence and CPL model were constrained. Later it was used (together with SNIa, CMB and BAO data) as a part of joint analysis in [18]. The results obtained were generally in agreement with those obtained by other authors with different methods. In particular, at the 2σ level they agree with the supernovae Ia results. Although the sample of suitable lenses (*i.e.* with good measurements of Einstein radii, source and lens redshifts and central velocity dispersions) has been rather small ($n = 20$ lenses) the ongoing SLACS survey is providing new strong lensing systems which is very encouraging for further applications of the method. The strategy adopted in SLACS survey is particularly important. The earlier searches were focused on source population (quasars) seeking for close pairs or multiples and checking if they are multiple images of a single source lensed by an intervening galaxy. Therefore a high lensing probability was an important selection factor there. Since lensing probability is proportional to the area of the Einstein ring, it means that two factors are crucial in this context. First, is the mass of the lens. This is the main reason why in vast majority of cases the lens is E/SO type galaxy. This could be understood since ellipticals being a latecomers in hierarchical structure formation are created in mergers of low-mass spiral galaxies. Hence they are more massive than spirals and the probability of their acting as lenses is higher. Second factor is the distance ratio $D_{\rm ls}/D_{\rm s}$. In details, this of course depends on the cosmological model, but it is maximal when the lens is located roughly half way between the source and the observer. The SLACS sample has an average $D_{\rm ls}/D_{\rm s}$ ratio equal to 0.58 with an rms scatter 0.15 [14]. While for their purpose (investigating galactic dynamics with strong lenses) it was advantageous, in our context it weakens the performance of the method. Therefore, having a sub-sample of lenses with the distance ratio $\mathcal{D}$ deviating from the mean more than rms in either direction would be beneficial and this criterion underlaid the sub-sample of $n = 7$ lenses in [17]. In this respect SLACS survey is encouraging. Namely, the SLACS survey is focused on possible lens population (massive ellipticals) with good spectroscopic data. Using SDSS templates, spectra are carefully checked for residual emission (at least three distinct common atomic transitions) coming from higher redshifts. Such candidates undergo image processing by subtracting parametrized brightness distribution typical for early type galaxies in order to reveal multiple images of the quasar [14]. Therefore, besides the obvious bonus of having central velocity dispersion measured, such strategy is better suited for discovering systems with larger $D_{\rm ls}/D_{\rm s}$ ratios which in turn can be used for testing cosmological models.

Not only the galaxies can act as lenses, their clusters — first virialized structures in the Universe — do the same. The cores of galaxy clusters have surface densities which are typically much larger than the critical surface density $\Sigma_{\rm cr}$ for multiple image production. Therefore, they are able to produce strongly lensed images of galaxies and quasars lying behind them. Such images manifest themselves as luminous arcs around clusters. The possibility of constraining cosmology with cluster strong lensing systems has been explored in the past *e.g.* [19, 20] and still remains a fruitful, fast developing field of research.

Analogously to the method outlined above for the galaxy lenses, the locations of images in cluster lensing systems also contain useful cosmological information. Namely, the image positions depend not only on the mass distribution, but also on the angular diameter distances between the observer, lens, and source. If more than one set of images is observed, the geometrical dependence may be exploited to probe the cosmological parameters even with a single cluster lens. One of the best studied cluster lensing system is Abell 1689. The mean redshift of this cluster is $z_{\rm l} = 0.184$ and it is one of the richest clusters in terms of the number density of galaxies in its core. In a recent paper by [21] this cluster was used to derive constraints on the cosmological parameters Ω_m and w. Based on images from the Advanced Camera for Surveys (ACS) this cluster is known to produce 114 multiple images from 34 unique background galaxies. This allowed [21] to use many observables like (5) from a single cluster. To be more specific instead using $\mathcal{D}^{\rm th}$ like in (5), they used quotients formed pairwise for background sources

$$\mathcal{D}^{\rm th}_{\rm cl} = \frac{\mathcal{D}^{\rm th}(z_{\rm l}, z_{\rm s1}; \boldsymbol{p})}{\mathcal{D}^{\rm th}(z_{\rm l}, z_{\rm s2}; \boldsymbol{p})}\,, \tag{6}$$

where: $z_{\rm l}$ is the cluster's redshift, $z_{\rm s1}$ and $z_{\rm s2}$ are redshifts of respective pair of sources.

Applying the following criteria: demand of good spectroscopic data for images and excluding regions where mass reconstruction gets poorer, from the initial 114 images, [21] selected finally 28 images which they further used to constrain cosmological parameters to $\Omega_m = 0.25 \pm 0.05$ $w = -0.97 \pm 0.07$. Even more promising is the idea of using a larger sample of cluster lensing systems. Such an approach has the advantage that results obtained from different lines of sight are statistically independent. As discussed by [22] competitive constraints can be obtained by combining at least 10 lenses with 5 or more image systems. One may, therefore, conclude that cluster strong lensing is becoming a very useful complementary tool for probing cosmic expansion history.

5. Conclusions

Strong gravitational lensing as an effect rooted deeply in General Relativity has great potential in constraining many aspects of gravitational physics. First of all, it is useful in studies of dark matter. It stems from the fact that gravitational lensing is sensitive to mass distribution regardless of its nature (whether they are baryonic or not). This is already a rich field being currently explored both theoretically and observationally.

In all known strong lensing systems producing multiple images, the population of sources is of cosmological nature (quasars or distant bright galaxies). In light of recent progress in modeling lensing galaxies, and considerable enrichment of observational data with reliable spectroscopic measurements allowing for determination of redshifts and central velocity dispersions, the new possibility opens up to use well studied strong lensing system for constraining cosmological model parameters. Although in the past there was certain scepticism about this technique, it is currently proving its effectiveness and in the future — having in mind development of ongoing and planned lens surveys — it will eventually evolve into a competitive technique for cosmography. This is very important, because of the dark energy problem (*i.e.* the puzzle of presently accelerating Universe). Currently, the only empirical way to address this issue is by refining the cosmography.

REFERENCES

[1] A.G. Riess *et al.*, *Astron. J.* **116**, 1009 (1998); S. Perlmutter *et al.*, *Astrophys. J.* **517**, 565 (1999).

[2] D.N. Spergel *et al.*, *Astrophys. J. Suppl.* **148**, 175 (2003); D.J. Eisenstein *et al.*, *Astrophys. J.* **633**, 560 (2005).

[3] G. Hinshaw *et al.*, *Astrophys. J. Suppl.* **180**, 225 (2009).

[4] B.E. Schaefer, *Astrophys. J.* **660**, 16 (2007).

[5] L.S. Finn, *Phys. Rev.* **D53**, 2878 (1996); M. Biesiada, *Mon. Not. R. Astron. Soc.* **325**, 1075 (2001).

[6] B. Bassett, R. Hlozek, *Baryon Acoustic Oscillations*, in *Dark Energy*, Ed. P. Ruiz-Lapuente, Cambridge University Press, 2010.

[7] L.I. Gurvits, *Astrophys. J.* **425**, 442 (1994).

[8] R.A. Daly, *Astrophys. J.* **426**, 38 (1994).

[9] M. Bonamente *et al.*, *Astrophys. J.* **647**, 25 (2006).

[10] P. Schneider, J. Ehlers, E.E. Falco, *Gravitational Lenses*, Springer-Verlag, Berlin 1992.

[11] P. Schneider, C.P. Kochanek, J. Wambsganss, *Gravitational Lensing: Strong, Weak and Micro*, in *Proceedings of the 33rd Saas-Fee Advanced Course*, Ed. G. Meylan, P. Jetzer, P. North, Springer-Verlag, Heidelberg 2006.

[12] M. Biesiada, *Strong Lensing Systems as Probes of Dark Energy Models and Non-standard Theories of Gravity*, in *Advances in Modern Cosmology*, Ed. A. Ghirbi, InTech Publ., 2011, p. 117.

[13] M. Biesiada, *Phys. Rev.* **D73**, 023006 (2006).

[14] L.V.E. Koopmans *et al.*, *Astrophys. J.* **649**, 599 (2006).

[15] L.V.E. Koopmans *et al.*, *Astrophys. J.* **703**, L51 (2009).

[16] C. Grillo, M. Lombardi, G. Bertin, *Astron. Astrophys.* **477**, 397 (2008).

[17] M. Biesiada, A. Piórkowska, B. Malec, *Mon. Not. R. Astron. Soc.* **406**, 1055 (2010).

[18] M. Biesiada, B. Malec, A. Piórkowska, *Res. Astron. Astrophys.* **11**, 641 (2011).

[19] B. Paczyński, K. Górski, *Astrophys. J.* **248**, L101 (1981).

[20] M. Sereno, *Astron. Astrophys.* **393**, 757 (2002).

[21] E. Jullo *et al.*, *Science* **329**, 924 (2010).

[22] J. Gilmore, P. Natarayan, *Mon. Not. R. Astron. Soc.* **396**, 354 (2009).