Noname manuscript No.
(will be inserted by the editor)

Time delay cosmography

Tommaso Treu · Philip J. Marshall

Received: date / Accepted: date

Abstract Here goes the abstract. mention blindness

Keywords First keyword · Second keyword · More

1 Introduction [TT]

What is time delay cosmography? Why is it cool? What is it good for? What are the challenges?

Blindness: with high precision comes greater responsibility. Extraordinary claims etc.

FIGURE: CARTOON OF LENSING, FROM SPACE WARPS WEBSITE? [PJM]

FIGURE: H0 AS A FUNCTION OF TIME (A CAUTIONARY TALE) [TT]

Cite Jackson 2015, Weinberg 2013, etc etc.

2 A brief history of time delay cosmography [TT]

Tommaso Treu
Department of Physics and Astronomy,
University of California,
Los Angeles, CA 90095, USA
E-mail: tt@astro.ucla.edu

Philip J. Marshall
Kavli Institute for Particle Astrophysics and Cosmology,
P.O. Box 20450, MS29,
Stanford, CA 94309, USA

Refsdal [1] first suggested that lens time delays could be used to measure absolute distances out to cosmological distances, and therefore the Hubble Constant to leading order. Unfortunately, no strong lensing systems were known at that time, and therefore his intuition remained purely theoretical for over a decade.

The prospects of using time delays for cosmography suddenly brightened in the late seventies, with the discovery of the first strongly lensed quasars [2]. Even though they were not the strongly lensed supernovae that Refsdal had in mind, quasars fluxes are sufficiently variable [3] that people were able to start to put Refsdal's idea in practice [4]. For completeness, we should mention that the first multiply imaged supernova has been discovered in 2014, fifty years afer Refsdal's initial suggestion [5], lensed by a foreground cluster of galaxies. The time delays are being measured at the time of this writing [6, 7]. However, it is unclear at the moment whether the cluster potential can be constrained with sufficient precision to yield interesting cosmological information [8]. Therefore, in this review, we will restrict our case to the much more common and better understood case of a variable quasar being lensed by a foreground elliptical galaxy.

Discovery and monitoring of lensed quasars continued in the eighties and nineties, powered by heroic efforts. By the end of the millennium the number of known strongly lensed systems was in double digits [9], and the first truly robust time delays were measured [10, 11].

The discovery of multiply imaged quasars finally took off at the beginning of the current Millennium with the improvement of panoramic search technology in dedicated or existing surveys [12–14].

The period of time delay cosmography was marred by controversies over systematic errors. The measurement of time delays was particularly controversial during the nineties as the quality of the early data allowed for multiple values [15], owing to the combined effects of gaps in the data, and microlensing noise in the optical light curves. This problem was definitely solved at the turn of the millennium, with the beginning of modern monitoring campaigns, characterized by high cadence, high precision, and long duration, both at optical and radio wavelengths [16–19], as illustrated in Figure 1. We discuss in more detail modern monitoring campaigns in Section 4.

Finally, when robust time delays started to become available, the focus of the controversy shifted to the modeling of the gravitational potential of the lens. Typically, in the mid ninenties, the only constraints available to modelers were the quasar image positions and to lesser extent flux ratios (limited by microlensing, variability and differential extinction). Thus, the best one could do was to assume some simple form for the lens potential like a singular isothermal sphere, thus breaking the mass sheet degeneracy, and to neglect the effects of structure along the line of sight. Given these necessary but oversimplistic assumptions, random errors grossly underestimated the total uncertainty, leading to measurements apparently inconsistent with those obtained by other groups or other techniques [21]. Since then, two methods have been pursued in order to break degeneracies in more flexible modeling of the lensing data

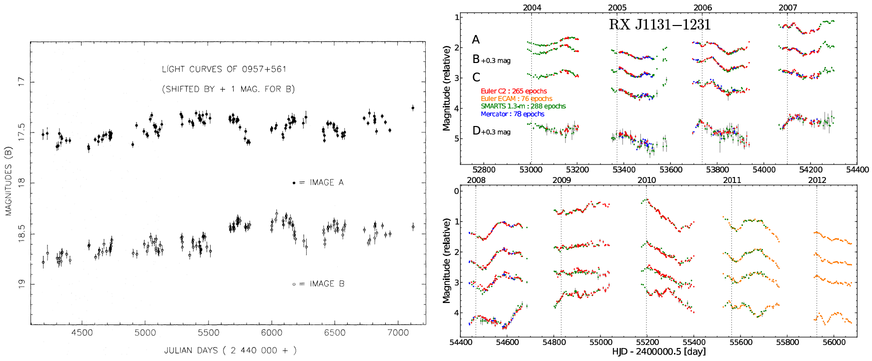

Fig. 1 Comparison between one of the early light curves (left panel; from [4] and a modern light curve from COSMOGRAIL (right panel; from [20]. Note the improved photometric precision, cadence, and duration of the light curves, allowing for unambiguous determination of the time-delay to within 1-2% precision.

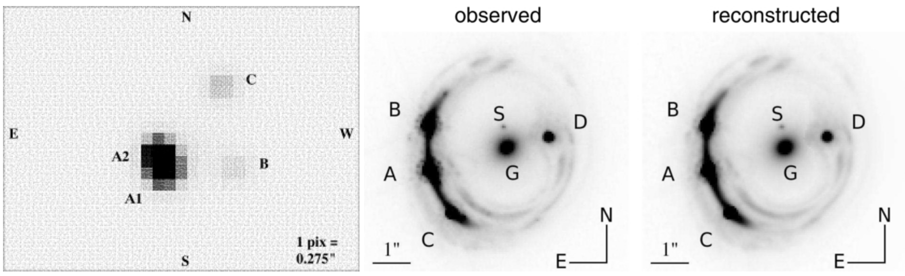

Fig. 2 Comparison between imaging data available in the nineties (left panel; from [11] and in the most recent studies (middle and right panel; from [29]). With modern data the structure of the quasar host galaxy can be modeled in great detail, providing thousands of constraints on the deflection angle, and thus on the derivatives of the gravitational potential.

and obtain realistic estimates on the uncertainties. One consists in using large samples of systems with relatively weak priors [22]. The other method consists in obtaining high quality data for each lens system, such as detailed imaging of the quasar host galaxy [23–25], or non-lensing data like the deflector stellar velocity dispersion [26] and the properties of galaxies along the line of sight [27, 28]. We discuss these approaches in Section 4.2. The astounding improvement in data quality over the past two decades is illustrated in Figure 2.

Ultimately, the controversies over systematic errors were essential to spur the community to overcome the difficulties and find ways to address them. This is a natural and probably inevitable part of the scientific process. However, the bitterness of some of those controversies during the ninenties and early naughts still resonates today. Unfortunately, some of the scientists that followed the field with excitement at that time, are still under the impression that strong lensing time delays are inherently inaccurate and imprecise. As we have briefly described here, and we will discuss in detail in the next sections, in the last twenty years the field has moved forward considerably implementing many solutions to the lessons learned the hard way.

3 Theoretical background [PJM]

Lensing, Fermat's principle and potential.

FIGURE: SCHEMATIC WAVEFRONT DIAGRAM FROM T&E15.

Time delay distance.

Importance of mass distribution in lens.

Model (mass-sheet) degeneracy and its generalizations

Importance of mass along the line sight - the universe is not Friedmann Lemaitre Robertson Walker.

POSSIBLE FIGURE: ILLUSTRATION OF LINE OF SIGHT EFFECTS? CARTOON COMPARING IDEALIZED UNIVERSE TO OVER/UNDER DENSE LINE OF SIGHT [PJM]

4 Modern Time delay distance measurement 2010+ [PJM]

4.1 Measuring time delays [PJM]

labelssec:tdmeasurements

Mention importance of blindness in all measurements.

4.1.1 Monitoring Observations

Fassnacht for B1608 COSMOGRAIL. Others?

4.1.2 Lightcurve Analysis

COSMOGRAIL TDC

4.2 Modeling the lens mass distribution [TT]

4.2.1 High Resolution Imaging Observations

4.2.2 Lens Modeling Techniques

4.2.3 The Role of Stellar kinematics

4.3 Lens environments and line of sight effects [PJM]

5 From time delay distances to cosmography [PJM]

6 Outlook [TT]

6.1 Precision [PJM

FIGURE: Forecasts for 10,50,100,1000 lenses for various cosmological models (w, wa+w0, curvature etc etc). CosmoSIS forecasts (ackn. Dave & Elise, ask them).

Check Jee et al.

6.2 Accuracy [PJM]

Discussion of systematic uncertainties

Time delay measurement. Light curve quality.

Lens mass modeling. Percent-level systematics due to model assumptions (ie MSD). IFU observations, resolved stellar kinematics. Ensembles.

Environment and line of sight

Time delay perturbations (someone's noise is somebody else's signal..)

The importance of blinding.

6.3 Cosmic complementarity [TT]

What's the point? Arent' other probes already doing it? Our place in the cosmology ecosystem. Discuss place relative to other distance indicators like Cepheids, BAO, Sne. Then complementarity with growth of structure probes like weak lensing, clusters etc etc. How important is H0?

Importance of multiple INDEPENDENT measurements for discovery of new physics.

7 Summary [TT]

Acknowledgements T.T. thanks the Packard Foundation for generous support through a Packard Research Fellowship, the NSF for funding through NSF grant AST-1450141, "Collaborative Research: Accurate cosmology with strong gravitational lens time delays". Thank people who give comments/input. Thank funding agencies.

References

1. S. Refsdal, MNRAS**128**, 307 (1964)
2. D. Walsh, R.F. Carswell, R.J. Weymann, Nature**279**, 381 (1979). DOI 10.1038/279381a0
3. C. Vanderriest, P. Felenbok, J. Schneider, G. Wlerick, A. Bijaoui, G. Lelievre, A&A**110**, L11 (1982)
4. C. Vanderriest, J. Schneider, G. Herpe, M. Chevreton, M. Moles, G. Wlerick, A&A**215**, 1 (1989)
5. P.L. Kelly, S.A. Rodney, T. Treu, R.J. Foley, G. Brammer, K.B. Schmidt, A. Zitrin, A. Sonnenfeld, L.G. Strolger, O. Graur, A.V. Filippenko, S.W. Jha, A.G. Riess, M. Bradac, B.J. Weiner, D. Scolnic, M.A. Malkan, A. von der Linden, M. Trenti, J. Hjorth, R. Gavazzi, A. Fontana, J.C. Merten, C. McCully, T. Jones, M. Postman, A. Dressler, B. Patel, S.B. Cenko, M.L. Graham, B.E. Tucker, Science **347**, 1123 (2015). DOI 10.1126/science.aaa3350
6. S.A. Rodney, L.G. Strolger, P.L. Kelly, M. Bradac, G. Brammer, A.V. Filippenko, R.J. Foley, O. Graur, J. Hjorth, S.W. Jha, C. McCully, A. Molino, A.G. Riess, K.B. Schmidt, J. Selsing, K. Sharon, T. Treu, B.J. Weiner, A. Zitrin, ArXiv e-prints (2015)
7. P.L. Kelly, S.A. Rodney, T. Treu, L.G. Strolger, R.J. Foley, S.W. Jha, J. Selsing, G. Brammer, M. Bradac, S.B. Cenko, M.L. Graham, O. Graur, A.V. Filippenko, J. Hjorth, T. Matheson, C. McCully, A. Molino, M. Nonino, A.G. Riess, K.B. Schmidt, B. Tucker, A. von der Linden, B.J. Weiner, A. Zitrin, ArXiv e-prints (2015)
8. T. Treu, G. Brammer, J.M. Diego, C. Grillo, P.L. Kelly, M. Oguri, S.A. Rodney, P. Rosati, K. Sharon, A. Zitrin, I. Balestra, M. Bradač, T. Broadhurst, G.B. Caminha, A. Halkola, A. Hoag, M. Ishigaki, T.L. Johnson, W. Karman, R. Kawamata, A. Mercurio, K.B. Schmidt, L.G. Strolger, S.H. Suyu, A.V. Filippenko, R.J. Foley, S.W. Jha, B. Patel, ApJ**817**, 60 (2016). DOI 10.3847/0004-637X/817/1/60
9. F. Courbin, P. Saha, P.L. Schechter, **608**, 1 (2002)
10. T. Kundic, E.L. Turner, W.N. Colley, J.R.I. Gott, J.E. Rhoads, Y. Wang, L.E. Bergeron, K.A. Gloria, D.C. Long, S. Malhotra, J. Wambsganss, ApJ**482**, 75 (1997). DOI 10.1086/304147
11. P.L. Schechter, C.D. Bailyn, R. Barr, R. Barvainis, C.M. Becker, G.M. Bernstein, J.P. Blakeslee, S.J. Bus, A. Dressler, E.E. Falco, R.A. Fesen, P. Fischer, K. Gebhardt, D. Harmer, J.N. Hewitt, J. Hjorth, T. Hurt, A.O. Jaunsen, M. Mateo, D. Mehlert, D.O. Richstone, L.S. Sparke, J.R. Thorstensen, J.L. Tonry, G. Wegner, D.W. Willmarth, G. Worthey, ApJL**475**, L85 (1997). DOI 10.1086/310478
12. I.W.A. Browne, et al., MNRAS**341**, 13 (2003). DOI 10.1046/j.1365-8711.2003.06257.x
13. M. Oguri, N. Inada, B. Pindor, M.A. Strauss, G.T. Richards, J.F. Hennawi, E.L. Turner, R.H. Lupton, D.P. Schneider, M. Fukugita, J. Brinkmann, The Astronomical Journal **132**, 999 (2006). DOI 10.1086/506019
14. A. Agnello, T. Treu, F. Ostrovski, P.L. Schechter, E.J. Buckley-Geer, H. Lin, M.W. Auger, F. Courbin, C.D. Fassnacht, J. Frieman, N. Kuropatkin, P.J. Marshall, R.G. McMahon, G. Meylan, A. More, S.H. Suyu, C.E. Rusu, D. Finley, T. Abbott, F.B. Abdalla, S. Allam, J. Annis, M. Banerji, A. Benoit-Lévy, E. Bertin, D. Brooks, D.L. Burke, A.C. Rosell, M.C. Kind, J. Carretero, C.E. Cunha, C.B. D'Andrea, L.N. da Costa, S. Desai, H.T. Diehl, J.P. Dietrich, P. Doel, T.F. Eifler, J. Estrada, A.F. Neto, B. Flaugher, P. Fosalba, D.W. Gerdes, D. Gruen, G. Gutierrez, K. Honscheid, D.J. James, K. Kuehn, O. Lahav, M. Lima, M.A.G. Maia, M. March, J.L. Marshall, P. Martini, P. Melchior, C.J. Miller, R. Miquel, R.C. Nichol, R. Ogando, A.A. Plazas, K. Reil, A.K. Romer, A. Roodman, M. Sako, E. Sanchez, B. Santiago, V. Scarpine, M. Schubnell, I. Sevilla-Noarbe, R.C. Smith, M. Soares-Santos, F. Sobreira, E. Suchyta, M.E.C. Swanson, G. Tarle, J. Thaler, D. Tucker, A.R. Walker, R.H. Wechsler, Y. Zhang, MNRAS**454**, 1260 (2015). DOI 10.1093/mnras/stv2171
15. W.H. Press, G.B. Rybicki, J.N. Hewitt, ApJ**385**, 416 (1992). DOI 10.1086/170952

16. C.D. Fassnacht, T.J. Pearson, A.C.S. Readhead, I.W.A. Browne, L.V.E. Koopmans, S.T. Myers, P.N. Wilkinson, ApJ**527**, 498 (1999). DOI 10.1086/308118
17. C.D. Fassnacht, E. Xanthopoulos, L.V.E. Koopmans, D. Rusin, ApJ**581**, 823 (2002). DOI 10.1086/344368
18. I. Burud, F. Courbin, P. Magain, C. Lidman, D. Hutsemékers, J.P. Kneib, J. Hjorth, J. Brewer, E. Pompei, L. Germany, J. Pritchard, A.O. Jaunsen, G. Letawe, G. Meylan, A&A**383**, 71 (2002). DOI 10.1051/0004-6361:20011731
19. A. Eigenbrod, F. Courbin, C. Vuissoz, G. Meylan, P. Saha, S. Dye, A&A**436**, 25 (2005). DOI 10.1051/0004-6361:20042422
20. M. Tewes, F. Courbin, G. Meylan, C.S. Kochanek, E. Eulaers, N. Cantale, A.M. Mosquera, P. Magain, H. Van Winckel, D. Sluse, G. Cataldi, D. Vörös, S. Dye, A&A**556**, A22 (2013). DOI 10.1051/0004-6361/201220352
21. C.S. Kochanek, P.L. Schechter, Measuring and Modeling the Universe p. 117 (2004)
22. M. Oguri, ApJ**660**, 1 (2007). DOI 10.1086/513093
23. C.R. Keeton, E.E. Falco, C.D. Impey, C.S. Kochanek, J. Lehár, B.A. McLeod, H.W. Rix, J.A. Muñoz, C.Y. Peng, The Astrophysical Journal **542**, 74 (2000). DOI 10.1086/309517
24. O. Wucknitz, A.D. Biggs, I.W.A. Browne, MNRAS**349**, 14 (2004). DOI 10.1111/j.1365-2966.2004.07514.x
25. S.H. Suyu, P.J. Marshall, M.P. Hobson, R.D. Blandford, MNRAS**371**, 983 (2006). DOI 10.1111/j.1365-2966.2006.10733.x
26. T. Treu, L.V.E. Koopmans, MNRAS**337**, L6 (2002). DOI 10.1046/j.1365-8711.2002.06107.x
27. C.R. Keeton, A.I. Zabludoff, ApJ**612**, 660 (2004). DOI 10.1086/422745
28. S.H. Suyu, P.J. Marshall, M.W. Auger, S. Hilbert, R.D. Blandford, L.V.E. Koopmans, C.D. Fassnacht, T. Treu, ApJ**711**, 201 (2010). DOI 10.1088/0004-637X/711/1/201
29. S.H. Suyu, T. Treu, S. Hilbert, A. Sonnenfeld, M.W. Auger, R.D. Blandford, T. Collett, F. Courbin, C.D. Fassnacht, L.V.E. Koopmans, P.J. Marshall, G. Meylan, C. Spiniello, M. Tewes, ApJL**788**, L35 (2014). DOI 10.1088/2041-8205/788/2/L35