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Time delay cosmography

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Abstract Here goes the abstract. mention blindness

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1 Introduction [TT]

The measurement of cosmic distances is central to our understanding of cosmography, i.e. the description of the geometry and kinematics of the universe. The discovery of the period luminosity relation for cepheids led to the realization that the universe is much bigger than the Milky Way and that it is currently expanding. Relative distance measurements based on supernova Ia light curves were the turning point in the discovery of the acceleration of the universe [1, 2].

In the two decades since the discovery of the acceleration of the universe, distance measurements have improved steadily. For example, the Hubble constant has now been measured to 3% precision [3, 4] while the distance to the last scattering surface of the cosmic microwave backgrond is now known to 1% precision [check]. This precision is more than sufficient for all purposes related to our understanding of phenomena occurring within the universe, like galaxy evolution.

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In spite of all this progress, the most fundamental question still remains unanswered. What is causing the acceleration? Is this *dark energy* something akin to Einstein's cosmological constant or is it a dynamical component? Answering this question from an empirical standpoint will require further improvements in the precision of distance measurements [5]. Many dedicated experiments are currently under way or being planned with ths goal in mind.

Precision, however, is not sufficient by itself. In addition to controlling the known statistical uncertainties, modern day experiments need to control stystematic errors in order to fullfill their potential, including the infamous unknow unknowns. The most direct way to demonstrate *accuracy* is to compare independent measurements with comparable *precision*.

Ideally, the comparison between independent measurements should be carried out blindly, so as to minimize experimenter bias. Two blind mutually blind measurements agreeing that the equation of state parameter w is not -1 would be a very convincing demonstration that the dark energy is not the cosmological constant. Conversely, the significant disagreement of two independent measurements, could open the door to the discovery of new physics.

In this review we focus on gravitational time delay as a tool for cosmography. Gravitational time delays are a natural phenomenon in general relativity and provide a direct and elegant way to measure absolute distances out to cosmological redshift. When the line of sight to a distant source of light is suitably well aligned with an intervening massive system, multiple images appear to the observer. The arrival time of the images depends on the interplay of the geometric and gravitational delays specific to the configuration. If the emission from the source is variable in time, the difference in arrival time is measurable, and can be converted into the so-called time delay distance $\mathrm{D}_{\Delta \mathrm{t}}$, a combination of angular diameter distances to the deflector and source. $\mathrm{D}_{\Delta \mathrm{t}}$is inversely proportional to the Hubble Constant H_0 and it is more weakly dependent on other cosmological parameters. The sensitivity to H_0 and independence to the local distance ladder method make time delays a very valuable cosmological tool for precise and accurate cosmology. As several authors have pointed out [6,**?**,5], achieving sub-percent precision and accuracy on the measurement of the Hubble constant is a powerful addition to stage III and IV dark energy experiments.

This review is organized as follows. In Section 1 we summarize the history of time delay cosmography up until the turn of the millennium, in order to give a sense of the early challenges and how they were overcome. In Section 3, we review the theoretical foundations of the method, in terms of the gravitational optics version of Fermat's principle. In Section 4 we describe in some detail the elements of a modern time delay distance measurement, emphasizing recent advances and remaining challenges. In Section 5 we elucidate the connection between time delay distance measurements and cosmological parameters, discussing complementarity with other cosmological probes. Section 6 critically examines the future of the method, discussing prospects for increasing the precision, testing for accuracy, and synergy with other future probes of dark energy. A brief summary is given in Section 7. Owing to space limitations, we could only present a selection of all the beautiful work that has been published on this topic in the past decades. We refer the readers to recent [7–13] and not-so-recent [14–18] excellent reviews and textbooks [19] for additional information and historical context.

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

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

2 A brief history of time delay cosmography [TT]

Refsdal [**?**, Ref64]irst suggested in 1964 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 [20]. Even though they were not the strongly lensed supernovae that Refsdal had in mind, quasars fluxes are sufficiently variable [21] that people were able to start to put Refsdal's idea in practice [22]. For completeness, we should mention that the first multiply imaged supernova has been discovered in 2014, fifty years afer Refsdal's initial suggestion [23], lensed by a foreground cluster of galaxies. The time delays are being measured at the time of this writing [24, 25]. However, it is unclear at the moment whether the cluster potential can be constrained with sufficient precision to yield interesting cosmological information [26]. 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 [15] , and the first truly robust time delays were measured [27, 28].

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 [29–31].

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 [32], 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 [33–36], as illustrated in Figure 1. We discuss in more detail modern monitoring campaigns in Section 4.

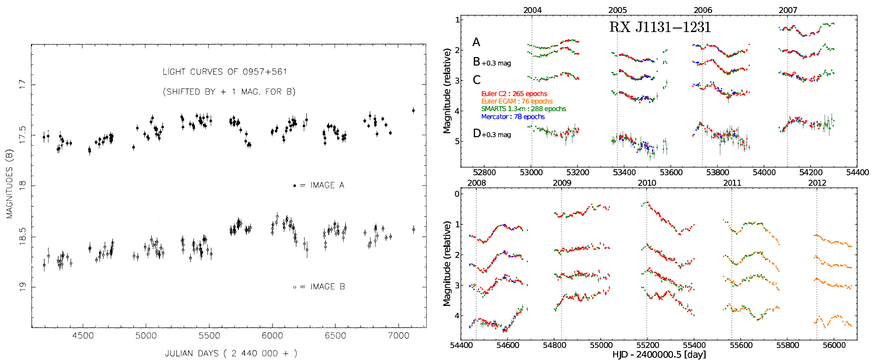

Fig. 1 Comparison between one of the early light curves (left panel; from [22] and a modern light curve from COSMOGRAIL (right panel; from [37]. Note the improved photometric precision, cadence, and duration of the light curves, allowing for unambiguous determination of the time-delay to within 1-2% precision.

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 nineties, 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 [16]. Since then, two methods have been pursued in order to break degeneracies in more flexible modeling of the lensing data and obtain realistic estimates on the uncertainties. One consists in using large samples of systems with relatively weak priors [38]. The other method consists in obtaining high quality data for each lens system, such as detailed imaging of the quasar host galaxy [39–41], or non-lensing data like the deflector stellar velocity dispersion [42] and the properties of galaxies along the line of sight [43, 44]. 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 nineties 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.

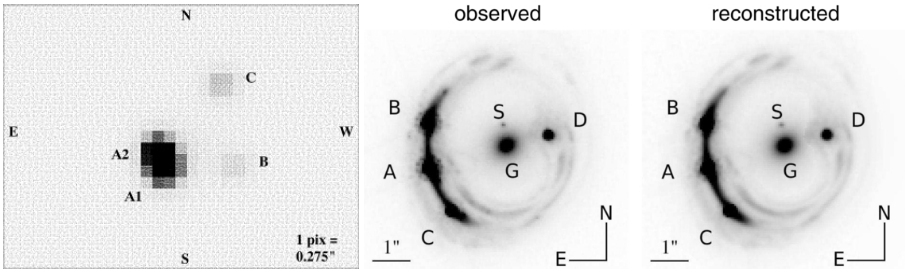

Fig. 2 Comparison between imaging data available in the nineties (left panel; from [28] and in the most recent studies (middle and right panel; from [45]). With modern data the structure of the quasar host galaxy can be modeled in great detail, providing thousands of constraints on the deflection angle, and thus on the derivatives of the gravitational potential.

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]

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References

1. A.G. Riess, A.V. Filippenko, P. Challis, A. Clocchiatti, A. Diercks, P.M. Garnavich, R.L. Gilliland, C.J. Hogan, S. Jha, R.P. Kirshner, B. Leibundgut, M.M. Phillips, D. Reiss, B.P. Schmidt, R.A. Schommer, R.C. Smith, J. Spyromilio, C. Stubbs, N.B. Suntzeff, J. Tonry, The Astronomical Journal **116**, 1009 (1998). DOI 10.1086/300499
2. S. Perlmutter, G. Aldering, G. Goldhaber, R.A. Knop, P. Nugent, P.G. Castro, S. Deustua, S. Fabbro, A. Goobar, D.E. Groom, I.M. Hook, A.G. Kim, M.Y. Kim, J.C. Lee, N.J. Nunes, R. Pain, C.R. Pennypacker, R. Quimby, C. Lidman, R.S. Ellis, M. Irwin, R.G. McMahon, P. Ruiz-Lapuente, N. Walton, B. Schaefer, B.J. Boyle, A.V. Filippenko, T. Matheson, A.S. Fruchter, N. Panagia, H.J.M. Newberg, W.J. Couch, The Supernova Cosmology Project, ApJ**517**, 565 (1999). DOI 10.1086/307221
3. A.G. Riess, L. Macri, S. Casertano, H. Lampeitl, H.C. Ferguson, A.V. Filippenko, S.W. Jha, W. Li, R. Chornock, ApJ**730**, 119 (2011). DOI 10.1088/0004-637X/730/2/119
4. W.L. Freedman, B.F. Madore, V. Scowcroft, C. Burns, A. Monson, S.E. Persson, M. Seibert, J. Rigby, ApJ**758**, 24 (2012). DOI 10.1088/0004-637X/758/1/24
5. D.H. Weinberg, M.J. Mortonson, D.J. Eisenstein, C. Hirata, A.G. Riess, E. Rozo, Phys.Rep.**530**, 87 (2013). DOI 10.1016/j.physrep.2013.05.001
6. E.V. Linder, Phys.Rev.D**84**(12), 123529 (2011). DOI 10.1103/PhysRevD.84.123529
7. M. Bartelmann, Classical and Quantum Gravity **27**(23), 233001 (2010). DOI 10.1088/0264-9381/27/23/233001
8. R.S. Ellis, Philosophical Transactions of the Royal Society of London Series A **368**, 967 (2010). DOI 10.1098/rsta.2009.0209
9. T. Treu, ARA&A**48**, 87 (2010). DOI 10.1146/annurev-astro-081309-130924
10. T. Treu, P.J. Marshall, D. Clowe, American Journal of Physics **80**, 753 (2012). DOI 10.1119/1.4726204
11. N. Jackson, eprint arXiv:1304.4172 (2013). URL http://adsabs.harvard.edu/abs/2013arXiv1304.4172J
12. N. Jackson, Living Reviews in Relativity **18** (2015). DOI 10.1007/lrr-2015-2
13. T. Treu, R.S. Ellis, Contemporary Physics **56**(1), 17 (2015). DOI 10.1080/00107514.2015.1006001. URL http://www.tandfonline.com/doi/abs/10.1080/00107514.2015.1006001
14. R.D. Blandford, R. Narayan, ARA&A**30**, 311 (1992). DOI 10.1146/annurev.aa.30.090192.001523
15. F. Courbin, P. Saha, P.L. Schechter, **608**, 1 (2002)
16. C.S. Kochanek, P.L. Schechter, Measuring and Modeling the Universe p. 117 (2004)
17. E.E. Falco, New Journal of Physics **7**, 200 (2005). DOI 10.1088/1367-2630/7/1/200
18. P. Schneider, C.S. Kochanek, J. Wambsganss, (2006). DOI 10.1007/978-3-540-30310-7
19. P. Schneider, J. Ehlers, E.E. Falco, *Gravitational Lenses* (Springer-Verlag Berlin Heidelberg New York, 1992)
20. D. Walsh, R.F. Carswell, R.J. Weymann, Nature**279**, 381 (1979). DOI 10.1038/279381a0
21. C. Vanderriest, P. Felenbok, J. Schneider, G. Wlerick, A. Bijaoui, G. Lelievre, A&A**110**, L11 (1982)
22. C. Vanderriest, J. Schneider, G. Herpe, M. Chevreton, M. Moles, G. Wlerick, A&A**215**, 1 (1989)
23. 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
24. 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)

25. 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)
26. 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
27. 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
28. 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
29. I.W.A. Browne, et al., MNRAS**341**, 13 (2003). DOI 10.1046/j.1365-8711.2003.06257.x
30. 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
31. 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
32. W.H. Press, G.B. Rybicki, J.N. Hewitt, ApJ**385**, 416 (1992). DOI 10.1086/170952
33. 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
34. C.D. Fassnacht, E. Xanthopoulos, L.V.E. Koopmans, D. Rusin, ApJ**581**, 823 (2002). DOI 10.1086/344368
35. 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
36. A. Eigenbrod, F. Courbin, C. Vuissoz, G. Meylan, P. Saha, S. Dye, A&A**436**, 25 (2005). DOI 10.1051/0004-6361:20042422
37. 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
38. M. Oguri, ApJ**660**, 1 (2007). DOI 10.1086/513093
39. 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
40. O. Wucknitz, A.D. Biggs, I.W.A. Browne, MNRAS**349**, 14 (2004). DOI 10.1111/j.1365-2966.2004.07514.x
41. 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
42. T. Treu, L.V.E. Koopmans, MNRAS**337**, L6 (2002). DOI 10.1046/j.1365-8711.2002.06107.x
43. C.R. Keeton, A.I. Zabludoff, ApJ**612**, 660 (2004). DOI 10.1086/422745
44. 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

45. 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