PROCEEDINGS OF SCIENCE

Gamma ghosts and gravitational lensing at gamma rays

Sara Buson* **on behalf of the *Fermi*-LAT Collaboration**
Università di Padova, Dip. di Fisica e Astronomia "G. Galilei", I-35131 Padova, Italy
INFN, Sezione di Padova, I-35131 Padova, Italy
E-mail: buson@pd.infn.it

Gravitational lensing represents an important resource since it is sensitive to all matter, whether it emits radiation or not. Besides, it has fundamental applications in astrophysics and cosmology: it not only efficiently traces mass distributions over cosmological distances but it can also be used to constrain the Hubble parameter (H_0) and the curvature of the Universe. The capabilities of the *Fermi* Gamma-Ray Telescope enable the exploration of lensing effects with gamma rays for the first time. Although *Fermi* lacks the spatial resolution necessary to resolve multiple lensed images, it has the advantage of enabling a continuous and dense sampling of flux variations in time. At these energies, powerful galaxies known as blazars are extremely variable and constitute the predominant source population. Therefore blazars are the favorite targets for lensing studies at gamma rays. Contextually, the recent detection of two known lensed systems with the *Fermi* Large Area Telescope (LAT), i.e. PKS 1830-211 and B0218+357, yielded the first measurements of lensing properties and H_0 through gamma rays while suggesting new interesting applications to investigate the blazar physics.

Science with the New Generation of High Energy Gamma-ray experiments, 10th Workshop - Scineghe2014
04-06 June 2014
Lisbon - Portugal

*Speaker.

1. Introduction

When a massive object (lens) lies close to the line of sight to a distant source, the paths of the source photons are bent by the lens gravitational field. This can result in distorted, magnified or multiple images of the same source. In the case when multiple images appear, the light from the source takes different paths to reach the observer. Since the travelled distances are different, this results in a time delay between the images. For time variable sources and in the case of not resolved multiple images, different photon arrival times result in a modification of the intrinsic time pattern that can be exactly repeated after a certain shift in time or, in most cases, distorted. This achromatic phenomenon is usually referred to gravitational lensing.

Gravitational lensing was already implicitly included in the theory of universal gravitation. Newton's original question "Do not Bodies act upon Light at a distance, and by their action bend its Rays, and is not this action strongest at the least distance?" draws back to 1704, but at that time it remained surrounded by a veil of uncertainty given that the finite speed of light was still not established. More than two centuries later, the first (strong/macro) gravitationally lensed object was discovered: TXS 0957+561, a quasar at a redshift of 1.41 whose image is split into two by the gravity of a foreground galaxy at a redshift of 0.39 (Walsh et al. 1979). Looking now at modern times, gravitational lensing appears to be a well established research field. Beside their intrinsic interest, gravitational lenses have exciting cosmological and cosmography applications (Blandford & Narayan 1986). For example, combining lens modelling with redshift and time delay measures it is possible to infer an estimation of the Hubble's constant (Refsdal 1964).

Even if widely capitalized at radio, optical and X-rays wavelengths, so far this technique has been only poorly investigated at gamma rays. The main reason for this has been the lack of a complete survey as well as the possibility to monitor the flux variations of sources at these frequencies. Nowadays, the unprecedented number of gamma-ray objects detected by the *Fermi* satellite (Atwood et al. 2009) opens, for the first time, a wide window to make significant progress in this field. In particular, the detection at gamma rays of two known lensed blazars (PKS 1830-211 and B0218+357; Ciprini 2010; Cheung et al. 2012) has proven that such systems can be observable also at high frequencies. The recent firm detection of gamma-ray flaring events related to gravitational lens effects in the blazar B0218+357 has led to the first measurement of the lensing time delay through gamma rays and, notably, has demonstrated that such independent measurements are possible. As a consequence, this paves the way for a new research stream looking for similar systems in other blazars, thus drawing the attention to surveys of active galactic nuclei (AGNs).

2. Gravitational lensing in the gamma-ray domain

Fermi-LAT is a pair-conversion telescope optimized for energies from 20 MeV to greater than 300 GeV (Atwood et al. 2009). Taking advantage of the LAT's large field of view ($\sim$2.4 sr), the *Fermi* observatory operating in scanning mode provides coverage of the full sky every three hours and offers a good opportunity to follow sources at gamma-ray energies.

Before the launch of *Fermi*, Atwood (2007) suggested that gravitational lensed systems could be observed with the LAT. Nowadays, the detection of gravitational lens effects imprinted in the gamma-ray light curve of B0218+357 has revealed such studies as a new promising frontier for pursuit at gamma rays. Even modern high-energy instruments like *Fermi* do not have the angular resolution to spatially resolve the multiple images produced by lensing effect. Nevertheless, the *Fermi*-LAT capability to continuously monitor with unprecedented statistics a large number of astrophysical objects enables for the first time the exploration of the high-energy time-domain. As a consequence, gamma-ray lensing effects can be recognised by identifying variability patterns repeated in the object's light curves. Nowadays the sample of known lensed systems detected at gamma rays includes only two objects, both blazars. In the following I will summarise the gamma-ray studies of these two objects and show that despite the limited sample, controversial results challenge our understanding of lensing effects and of blazar systems themselves.

2.1 PKS 1830-211: the puzzling lens

The flat spectrum radio quasar PKS 1830-211 was discovered as a single source in the Parkes catalog, but later radio observations by the Very Large Array and Australian Telescope Compact Array (ATCA) clearly revealed two sources, one in the north-east and one in the south-west, separated by 0.98$''$ and connected by an Einstein ring (Pramesh Rao & Subrahmanyan 1988; Jauncey et al. 1991). A time delay of $\Delta t = 26^{+4}_{-5}$ days was measured from the light curves of the two lensed images by Lovell et al. (1998) with ATCA and consistent values were found later by Wiklind & Combes (2001).

Among the *Fermi* gamma-ray blazars, PKS 1830-211 ($z = 2.507$, Lovell et al. 1998) is the third most distant object detected in large flaring activity so far by the LAT behind TXS 0536+145 ($z = 2.69$, Sowards-Emmerd et al. 2005) and B3 1343+451 ($z = 2.534$, Linford et al. 2011). Enhanced activity from the gamma-ray point source positionally consistent with PKS 1830-211 was initially observed in 2010 October (Ciprini 2010). Subsequent exceptional and repeated flux increments recorded over years offered a good opportunity to investigate the gravitational lensing signatures.

Figure 1 displays the gamma-ray (E > 200 MeV) light curve of PKS 1830-211 in weekly bins, from 2008 August 4 to 2011 July 25 (MJD 54682.65 to 55767.65). The main flaring activity was caractherized by three flaring periods indicated in Figure 1: near the end of 2009 the period indicated as "A" interval contains the first gamma-ray brightening seen by the LAT; the "B" and "C" intervals correspond to the subsequent two largest flux increments that took place at the end of 2010. Analysis of its initial gamma-ray flaring activity led to a claimed LAT delay measurement of $\Delta t_\gamma = 27.1 \pm 0.6$ days (Barnacka et al. 2011), in agreement with the radio derived delay (Lovell et al. 1998). Subsequent detailed analysis of a more extended *Fermi*-LAT dataset did not confirm lensing signatures in the light curve (Abdo et al. 2014). The discrete autocorrelation function (DACF) applied to the 3-year LAT dataset shown in Figure 2 shows a clear 19-day peak, but this does not provide enough evidence of a detection of delayed events induced by lensing as it could be produced by the timescale of the two main flare events (the peaks in the "B" and "C" intervals).

The latter outcome constitutes a challenge in light of the previous well-established delay measurements for PKS 1830-211 and of the fact that gravitational lensing is supposed to be achromatic. While microlensing due to individual stars in the main lens galaxy is expected to be negligible in many cases, additional lensing effects due to nearby galaxies cannot be excluded. It is worth to note also that ALMA found a remarkable frequency-dependent behavior of the flux ratio of the two blazar images during the gamma-ray flares (Martí-Vidal et al. 2013). Moreover if the gamma-ray emission region is displaced from the radio-band emission region, the flux ratio could be different in the gamma-ray and radio bands. This would explain the lower limit of ∼6 derived for the gamma-ray flux ratio between the two lens images, which is significantly larger than the flux ratio observed in radio bands (Abdo et al. 2014).

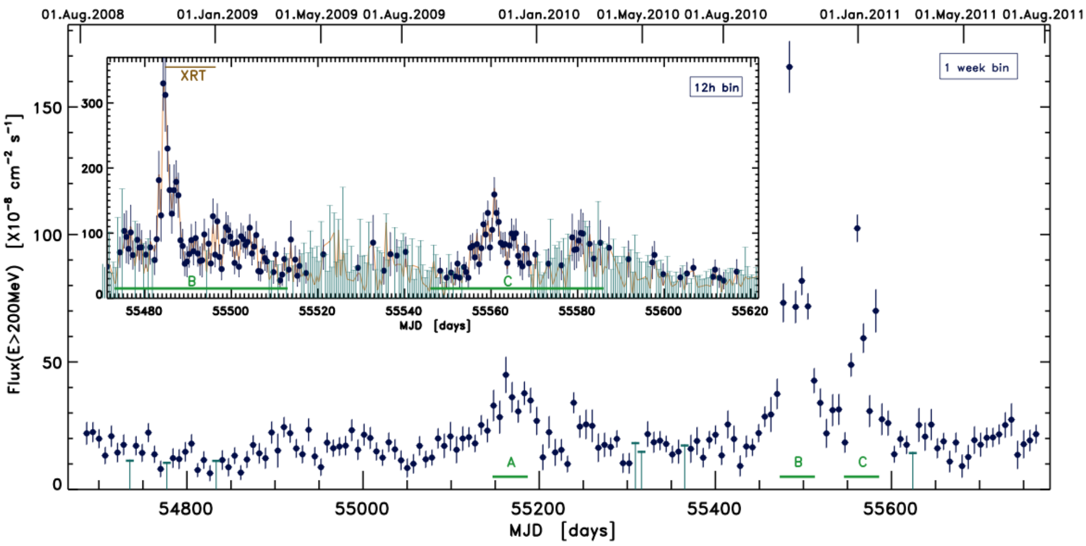

Figure 1: *Main panel*: 3-year (1085 days) *Fermi*-LAT gamma-ray flux (E>200 MeV) light curve of PKS 1830-211 in weekly bins, extracted with gtlike fit in each bin from 2008 August 4 to 2011 July 25 (MJD 54682.65 to 55767.65). *Inset panel*: gtlike light curve detailing the ∼150 day period (MJD interval: 55471-55621, i.e. from 2010 October 2 to 2011, March 1) flux light curve extracted with 12-hour bins and containing the "B" and "C" intervals when the main outburst of 2010 October and the second largest, and double-peaked, flare of 2010 December and 2011 January occurred. In both panels vertical lines refer to 2-σ upper limits on the source flux; from Abdo et al. (2014).

2.2 B0218+357: the timely delay

B0218+357 is a blazar at $z = 0.944$ (Cohen et al. 2003) lensed by a galaxy at redshift $z = 0.6847$ (Browne et al. 1993). In the radio band, a double image separated by 335 milli-arcseconds and an Einstein ring (O'Dea et al. 1992; Patnaik et al. 1993) is observed, with a brighter western A and fainter eastern B images. The delay between the two images has been measured in radio as $\Delta t_r = 10.5 \pm 0.2$ (Biggs et al. 1999), 10.1 ± 0.8 days (Cohen et al. 2000), and two possible values $\Delta t_r = 9.9^{+4.0}_{-0.9}$ or 11.8 ± 2.3 days by Eulaers & Magain (2011).

Fermi-LAT measured gamma-ray fluxes, $F_\gamma = (1.00 \pm 0.07) \times 10^{-7}$ photons cm^{-2} s^{-1} over its first 2-years of observations (2FGL J0221.0+3555; Nolan et al. 2012). Beginning in 2012 August, gamma-ray flares from B0218+357 were observed (Ciprini 2012; Giroletti et al. 2012; Cheung et al. 2012) and lasted for several months. Cheung et al. (2014) used this dataset to derive the first clear measurement of the lensing delay with the LAT. Their study yielded a competitive delay estimate of 11.46 ± 0.16 days (see Figure 4) and a flux ratio of the A/B images of about unity (see Figure 3). This observed gamma-ray flux ratio is smaller than what previously found in the radio band, where Biggs et al. (1999) and Cohen et al. (2000) reported values of the order of about 3-4. The discrepant flux ratios could be due to superposing strong flaring activities dominating

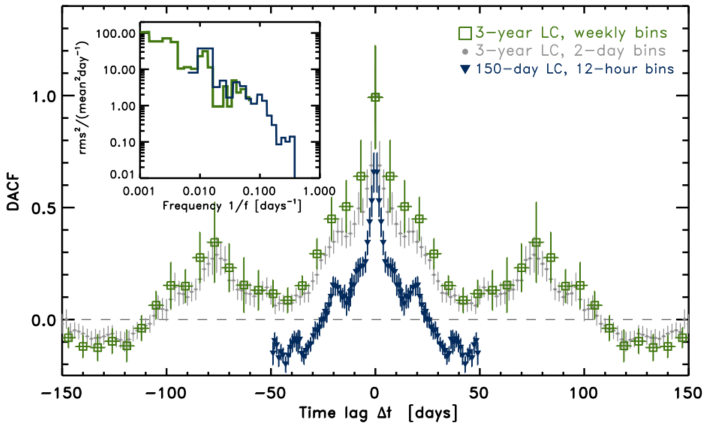

Figure 2: *Main panel*: DACF of the 3-year, weekly bin (green square open points) 2-day bin (tiny light gray points) and 150-day, 12-hour bin (blue small triangles) LAT flux light curves shown in Figure 1. *Inset panel*: Power density spectra, normalized to fractional variance per frequency unit f calculated for the 3-year weekly and the 150-day, 12-hour bin LAT light curves. From Abdo et al. (2014).

the gamma-ray fluxes that might have contaminated the gamma-ray ratio estimate or microlensing effects coming into play. The same explanation could be invoked to interpret some sharp outlying flux increments with no correspondent delayed counterpart found in the light curve (these features are indicated as asterisks in Figure 2 of Cheung et al. 2014).

Interestingly the different delay measured with radio and gamma rays could also be interpreted as a displacement between the radio and the gamma-ray emitting regions. The inferred offset is of ~ 70 pc, (projected), but this number seems extreme given that the common values found in other blazars jets is ~ 7 pc.

During the 2012 flaring activity there was no significant change in the spectrum, being the photon index consistent with the average $\Gamma = 2.30 \pm 0.03$ over the first ~ 4 years of LAT observations. Renewed flaring activity has been recently observed in 2014 July (Buson & Cheung 2014). This time an unusual hard spectra denoted the enhanced phase with $\Gamma < 2$. The *Fermi*-LAT alert prompted observations in other wavelengths, such as at optical, X-rays and very-high energies (VHE, > 100 GeV). Remarkably, thanks to this exceptionally hard spectral signature, B0218+357 has been significantly ($> 5\sigma$) detected at VHE by the MAGIC telescopes, establishing this source as the first lensed system and the most distant blazar observed so far at TeV energies (Mirzoyan 2014).

3. Future perspectives

So far gravitational lens studies have been primary guided by the detection and study of multiple images of the same object. As demonstrated by Cheung et al. (2014), a complementary approach has been validated exploiting the *Fermi*-LAT dataset in the still poorly studied time domain and shows to be a promising research ground.

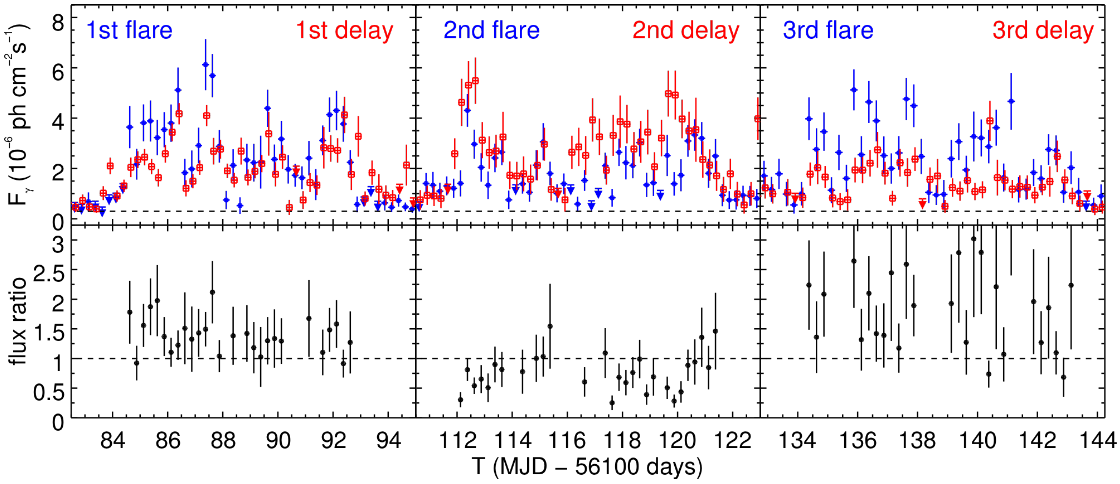

Figure 3: *Top panels*: B0218+357 6-hr binned lightcurves for the three flares (filled blue) and delayed emission shifted by –11.46 days (open red). *Bottom panels*: individual observed flux ratios (dashed line drawn at ratio = 1 for reference) in the corresponding upper panels; error bars are symmetric and the third panel was cropped in order to display a common range; from Cheung et al. (2014).

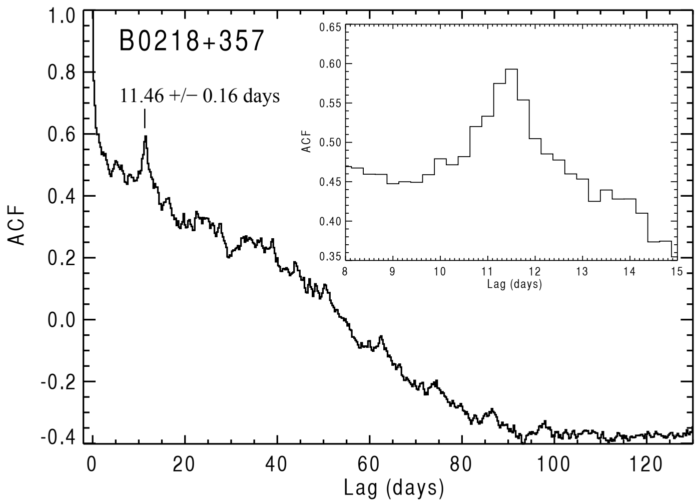

Figure 4: *Main panel*: Auto-correlation function computed for the 6-hr binned LAT lightcurve of the 265-day flaring interval. *Inset panel*: Zoom around the best-fit indicated lag peak; from Cheung et al. (2014).

The *Fermi*-LAT collaboration is working on a refined event-level analysis, `Pass 8` (Atwood et al. 2013), which will have a larger acceptance, a better Point Spread Function at high energies and a wider energy range. This will greatly improve the study of time-domain high-energy astronomy providing more accurate, finer binned light curves to better pinpoint inherent and lensing-induced variability. Besides, `Pass 8` will ensure a significant reduction in background contamination, an increased effective area and as well as lower systematic errors. The number of detected objects at gamma rays will increase, hopefully enlarging the gamma-ray lensed-system population.

The investigation of lensing properties with gamma rays possibly will led to new lens delay estimates and in turn to independent constrain in the Hubble constant and the curvature of the Universe. They will serve as fundamental complement for other cosmological probes, and further be used to mitigate unknown systematics.

Additional applications among the capabilities of this new approach are the discovery of new lensed systems, with smaller separation than resolvable in current lens survey finding images and yet unidentified southern hemisphere sources, where lens surveys are still incomplete. Besides, this technique would be capable to investigate the existence of lens with no detected lensing galaxy, invoking the interesting, more exotic, possibility of galaxy-sized condensations of dark matter.

Some authors have suggest that the different behaviour of lensing properties observed so far in the separate energy bands could be related to blazar intrinsic properties, in particular to differing physical mechanisms. For instance, gravitational microlensing involving the innermost regions of blazars would be an appealing means to locate and investigate the gamma-ray emitting region, otherwise inaccessible to conventional techniques (Barnacka et al. 2014). In this context, studying how magnification ratios in different frequencies arise from spatially distinct emission regions can probe differing multi-frequency jet structures (Martí-Vidal et al. 2013).

Noteworthy, the detection of VHE photons from B0218+357 directs now also the interest of ground-based Cherenkov telescopes to these objects, in particular of the upcoming CTA (Actis et al. 2011). In the case of distant sources, the anticipated signal, announced could be used to schedule ad hoc observations of the object, enabling to collect a dataset capable to infer unprecedented limits on the extragalactic background light abundance and, consequently, on the galaxy and star formation history.

Acknowledgments

The *Fermi*-LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2014, Astrophys. J., 799, 143

Actis, M., Agnetta, G., Aharonian, F., et al. 2011, Experimental Astronomy, 32, 193

Atwood, W., Albert, A., Baldini, L., et al. 2013, arXiv:1303.3514

Atwood, W. B. 2007, in the Les Houches Winter School "The Violent Universe," CEA-Saclay

Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, Astrophys. J., 697, 1071

Barnacka, A., Geller, M. J., Dell'antonio, I. P., & Benbow, W. 2014, Astrophys. J., 788, 139

Barnacka, A., Glicenstein, J.-F., & Moudden, Y. 2011, Astron. Astrophys., 528, L3

PoS(Scineghe2014)016

Biggs, A. D., Browne, I. W. A., Helbig, P., et al. 1999, Mon. Not. R. Astron. Soc., 304, 349

Blandford, R. & Narayan, R. 1986, Astrophys. J., 310, 568

Browne, I. W. A., Patnaik, A. R., Walsh, D., & Wilkinson, P. N. 1993, Mon. Not. R. Astron. Soc., 263, L32

Buson, S. & Cheung, C. C. 2014, The Astronomer's Telegram, 6316, 1

Cheung, C. C., Larsson, S., Scargle, J. D., et al. 2014, Astrophys. J. Lett., 782, L14

Cheung, C. C., Ojha, R., Orienti, M., & Wood, D. L. 2012, The Astronomer's Telegram, 4411, 1

Ciprini, S. 2010, The Astronomer's Telegram, 2943, 1

Ciprini, S. 2012, The Astronomer's Telegram, 4343, 1

Cohen, A. S., Hewitt, J. N., Moore, C. B., & Haarsma, D. B. 2000, Astrophys. J., 545, 578

Cohen, J. G., Lawrence, C. R., & Blandford, R. D. 2003, Astrophys. J., 583, 67

Eulaers, E. & Magain, P. 2011, Astron. Astrophys., 536, A44

Giroletti, M., Orienti, M., & Cheung, C. C. 2012, The Astronomer's Telegram, 4371, 1

Jauncey, D. L., Reynolds, J. E., Tzioumis, A. K., et al. 1991, Nature, 352, 132

Linford, J. D., Taylor, G. B., Romani, R. W., et al. 2011, Astrophys. J., 726, 16

Lovell, J. E. J., Jauncey, D. L., Reynolds, J. E., et al. 1998, Astrophys. J. Lett., 508, L51

Martí-Vidal, I., Muller, S., Combes, F., et al. 2013, Astron. Astrophys., 558, A123

Mirzoyan, R. 2014, The Astronomer's Telegram, 6349, 1

Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, Astrophys. J. Suppl. S., 199, 31

O'Dea, C. P., Baum, S. A., Stanghellini, C., et al. 1992, Astronom. J., 104, 1320

Patnaik, A. R., Browne, I. W. A., King, L. J., et al. 1993, Mon. Not. R. Astron. Soc., 261, 435

Pramesh Rao, A. & Subrahmanyan, R. 1988, Mon. Not. R. Astron. Soc., 231, 229

Refsdal, S. 1964, Mon. Not. R. Astron. Soc., 128, 307

Sowards-Emmerd, D., Romani, R. W., Michelson, P. F., Healey, S. E., & Nolan, P. L. 2005, Astrophys. J., 626, 95

Walsh, D., Carswell, R. F., & Weymann, R. J. 1979, Nature, 279, 381

Wiklind, T. & Combes, F. 2001, in Astronomical Society of the Pacific Conference Series, Vol. 237, Gravitational Lensing: Recent Progress and Future Go, ed. T. G. Brainerd & C. S. Kochanek, 155