Extragalactic Extinction Laws and Quasar Structure from Colour Differences between Images of Lensed Quasars

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Abstract

The action of the mean gravitational field of an intervening galaxy sufficiently aligned with a distant quasar can form several images of this object (multiple imaged quasar). Random fluctuations of the gravitational field induced by the highly inhomogeneous granulation of stars or in dark matter clumps of the lens galaxy mass distribution can subdivide the images in scales of microarcsecs (microlensing by stars) or miliarcsecs (mililensing by dark matter clumps). Anomalies induced by microlensing in the flux brightness of the images can be very strong for small sources or be averaged out by sufficiently large sources. Thus, microlensing magnification of the flux of a radially stratified source can be wavelength dependent (chromaticity). On the other hand, in their path through the lens galaxy the photons of the quasar images are also affected by the patchily distributed interstellar medium (dust extinction). Thus, the wavelength dependence of extinction can be obtained from the flux ratios between two images.

In this work we review the use of quasar spectra to disentangle microlensing and dust extinction (based in the comparison between the continuum and emission line flux ratios for different images of the quasar) discussing the impact of the intrinsic source variability in this procedure. We will also review some results derived using this technique like the low fraction of mass in MACHOS in the dark halos of lens galaxies, the unexpected large sizes of the accretion disks present in the central region of lensed quasars or the derivation of extinction curves in the extragalactic domain that reveals a variability in dust properties similar to the one found in the Local Group of galaxies.

1. Introduction

One of the most successful experimental schemes used in modern physics is that of the "optical bench". A source emits either photons, alpha particles, neutrons, or any other "bullets" that interact with a test object and are afterwards detected by the observer. This scheme allows the researcher to change and move any of the constituents of the experiment to check the current hypothesis about their nature.

Sources and test objects in the Universe are so big that the astronomer has not the possibility of manipulate them. However, in some rare cases a distant source (typically a quasar) appears almost aligned with a galaxy and the observer can measure the deflection of the light rays caused by the gravitational field of the galaxy. This is a gravitational lens system (or simply, a gravitational lens), an astronomical optical bench that can be used as a tool to study both, the quasar and the deflecting galaxy.

When the alignment between quasar and galaxy is good enough the light can find several paths to reach the observer forming a system of multiple images (macroimages) of the quasar, usually two or four. A very simple gravity model of "Maxwellian" galaxy (Singular Isothermal Sphere, SIS) plus a perturbation (external shear) is enough, in the majority of lens systems, to give good fits to the positions of the source and of the images. The same model also predicts the relative fluxes between images (relative magnifications). However, these predictions fail in many cases to reproduce the observed flux ratios (magnification anomalies).

This model fails because it only gives a mathematical description of the mean gravitational potential and does not take into account that real galaxies are very inhomogeneous at several scales. In first place, the visible constituents of galaxies, the stars (substellar mass objects have also been detected, Schild 1996), are almost point-like producing random, local, and very strong fluctuations of the gravitational potential that can bend the trajectory of light rays giving rise to the subdivision of macroimages in several subimages separated by micro-arcseconds. This phenomenum is quasar microlensing. The spatial scale of the magnification fluctuations associated with microlensing can be extremely small in some regions of the source plane (formally the gradient of magnification tends to infinity across caustic curves; see Figure 1a). Thus, small sources (even if they are very small) can be differentially magnified when they cross a caustic (they are scanned in one direction by the caustic). On the contrary, big sources sufficiently larger than the average scale of magnification fluctuations do not change its magnification due to microlensing. Sources of intermediate sizes will be inhomogeneously magnified by the irregular magnification pattern induced by microlensing (see Figure 1b).

Then, microlensing magnification depends on the size of the source. The standard model for quasar continuum sources is the thin accretion disk (Shakura & Sunyaev 1973) that predicts that the temperature and, consequently, the dominant wavelength emission vary with radial distance. Thus, the inhomogeneous microlensing magnification can induce a wavelength dependent magnification of the source (chromaticity). In general, this chromaticity will induce higher magnifications in the blue continua that arise from smaller regions, than in the red ones.

In the second place, the interstellar medium is patchily populated with atoms, molecules (gas) and solid particles and aggregates (dust grains) that can scatter and absorb the photons modifying the relative luminosity of the images. Two images crossing the lens galaxy in two different places can suffer in a different measure the effects of dust extinction. Thus, as far as the images are intrinsically identical, we can extend the standard pair method devised to determine extinction laws in the Milky Way (Massa et al. 1983), to the extragalactic domain obtaining the wavelength dependence of extinction from the flux ratio between two images (Nadeau et al. 1991).

In the third place, the dark component of galaxies can have, according to CDM models, a substructure of clumps with different masses and compactness that also will modify the gravitational potential (at larges scales) giving rise to flux anomalies and displacements in the images positions (some interesting statistical tests and simulations can be found in Kochanek & Dalal, 2004, Xu et al. 2009 and references therein). Although this is a very important issue for gravitational lensing, it is by far less explored and we will focus in the study of microlensing and extinction. A first step in this study is to separate both effects in the chromaticity of the flux ratio between images of a lensed quasar. We will review here the use of quasar spectra to this purpose.

2. Disentangling chromatic microlensing and dust extinction from quasar spectroscopy

As discussed above, both effects, microlensing of a radially stratified source and dust in the lens galaxy can induce chromaticity in the flux ratio between two images of a lensed quasar. How can we disentangle them to study extinction laws and the source structure? A possibility to do this is to find a region sufficiently large as to be insensitive to microlensing but enough small as to suffer the same extinction as the accretion disk. In this way we can use the flux ratio between the images of the large region to define the wavelength dependence of extinction. If we remove this chromaticity associated with extinction from the flux ratio of the images of the accretion disk we will have the wavelength dependence of microlensing.

Mathematically, the wavelength dependent flux of one of the images of a small region that can be affected by microlensing and extinction is given in magnitudes by,

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where is the intrinsic flux of the source with the wavelength corrected by the redshift of the source. The dependence of the intrinsic flux on $t-\Delta t_i$ reflects that the source can be intrinsically variable and that there is a relative time delay in the arrival of the signal to a given image. is the magnification induced by the mean gravitational field of the lens galaxy and the fluctuation in the magnification induced by microlensing that can be wavelength dependent. Finally, $A_i(\lambda/(1+z_l))$ is the extinction caused by the dust in the lens galaxy. If we consider a pair of images, A and B, the flux ratio is given (in magnitudes) by

On the other hand, for a region sufficiently large as to be insensitive to microlensing but enough small as to suffer the same extinction than the accretion disk we have,

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In this case, the region is assumed to be of constant intrinsic flux. For this region the flux ratio is given by

This flux ratio has the same dependence on the mean magnification and on the extinction that the flux ratio corresponding to the small region but is not affected by extinction.

Subtracting this zero microlensing baseline, we cancel the terms corresponding to the mean gravitational field magnification and to the extinction, ,

This is the differential microlensing curve between two images plus an intrinsic variability term. This term vanishes if we combine observations taken at epochs with a time difference equal to the $\Delta t_A - \Delta t_B$ lag between the images. If these observations are not available the relevance of the intrinsic variability term will, statistically, increase with the time lag between the images. Structure functions obtained for the quasars continuum from the SDSS (Yonehara et al. 2008) indicate that for the optical, the intrinsic variability term will correspond to $\approx 0.06 - 0.1$ mag for the typical time delay (1 month). Thus, the intrinsic variability term can be significant only for microlensing measurements of about 0.1 mag. In any case, note that in the optical wavelength range the variability in different photometric bands seems to be correlated and, hence, the differences in chromaticity induced by intrinsic variability are considerable smaller (Yonehara et al. 2008).

The region enough large to be insensitive to microlensing can typically be the Narrow Line Region (NLR) and the small region of the quasar continuum source. However, other options can be interesting like considering the high ionization Broad Emission Lines (BEL) fluxes for the small region or the low ionization BEL fluxes for the large region.

3. Results

3.1. Extragalactic MACHOS

The ignorance about the nature of the greater part of the matter in the halos of galaxies (dark matter) is one of the central problems in astrophysics. It has been suggested that the dark matter in the Milky Way halo can be constituted by massive compact objects (massive compact halo objects, MACHOS) that can act as microlenses (Paczynski 1986) magnifying stars in the LMC. During more than 10 years several experiments have analyzed the photometric monitoring of millions of stars looking for microlensing events that can give information about the characteristics and abundance of MACHOS. However, the estimates for the fraction of mass in MACHOS in the Milky Way (and also in M 31) disagree with results from less than 8% to 90% (Alcock et al. 2000, Belokurov et al. 2004, Tisserand et al. 2007, Griest & Thomas 2005, Calchi Novati et al. 2005, de Jong et al. 2006).

It is conceptually straightforward to extend the use of microlensing to study the dark matter composition to the extragalactic domain considering multiple imaged quasars (see the review by Wambsganss 2006). However, a statistical study of quasar microlensing based in photometric monitoring (see e.g., Webster et al. 1991, Morgan et al. 2008) meets some problems like the large timescales for microlensing variability (of the order of years) and the above commented lack of a baseline for no microlensing magnification (see e.g. Kochanek 2004). An alternative possibility is to detect flux ratio anomalies between the images of quasars that can be compared with simulated magnification probability distributions (Witt et al. 1995, Schechter & Wambsganss 2002, 2004). These anomalies can be detected calculating theoretically the intrinsic flux ratios from models of the lenses (Schechter & Wambsganss 2004) and making some estimates for the extinction or, in the way described in this paper, experimentally by using the emission line flux ratios to determine the baseline for no microlensing. The second approach has been developed by Mediavilla et al. (2009) using spectra of 29 pairs of lensed quasars obtained from the literature. They found a moderate (in magnification amplitude) incidence of microlensing events. A maximum likelihood test, based on microlensing simulations for different values of the fraction of mass in MACHOS, reveals that only a 5% of the mass of the dark halos can be in compact objects for sources of a few light-days of radius. In principle this can correspond to the normal population of stars and MACHOS would be not required to explain the observed microlensing. However, the fraction of compact objects can increase to a 10-15% for a 10 light-days radius source (Mediavilla et al. 2009) that, in light of recent measurements (see next section), can be not so rare. Due to the degeneracy between source size and microlens mass (see e.g. Mediavilla et al. 2009), a population of substellar mass objects might also explain the observed microlensing statistics with a substantially higher fraction of mass in compact objects (see also Schild 1996).

3.2. Quasar structure

The standard model for quasars is based in the existence of super massive black-holes surrounded by accretion disks transforming matter in energy at the highest known rates of efficiency. The observational approach to this exotic physics is, however, rather limited by the very small angular size of these structures. Due to the faculty of microlensing to scan a source irrespective of how small it is, this phenomenon has been used in several ways to study the size and radial stratification of accretion disks. The most widely used approach is based in photometric monitoring of multiple imaged quasars. The rate and amplitude of the flux variability induced by microlensing can be used to constrain the disk size. This procedure has been used with success in several objects (e.g. Kochanek 2004, Morgan et al. 2010, Poindexter et al. 2010). Other option, according to the aim of this work, is the detection and study of chromaticity induced by microlensing in the SED of the images to model the source. This option can be based in multi band photometry, sometimes combining the X-Ray, optical and IR spectral ranges (Pooley et al. 2007, Anguita et al. 2008, Agol et al. 2009, Bate et al. 2009, Floyd et al. 2009, Blackburne et al. 2010), although the lack of definition of the baseline for no microlensing magnification must be corrected in some way.

The study of the SED can be better based in quasar spectra that, as commented above, allows in a consistent way to disentangle microlensing and extinction using the quasar emission lines (Vanderriest 1990). This approach has been applied to a few objects. In HE 1104-1805 Wisotzki et al. (1993, 1995) found that the emision line flux ratios were approximately constant but that the continuum flux ratio shows a wavelength dependence that can be interpreted as microlensing. In HE 0512-3329, Wucknitz et al. (2003) were able to separate extinction from microlensing using the flux ratio between several emission lines. Using a coarse spectroscopy based in narrow band photometry, Mosquera et al. (2009, 2011) were able to separate the emission lines from the continuum in Q 2237+0305 and in HE 0435−1223 finding chromatic microlensing. These authors modelled the accretion disk as a Gaussian source and simulate microlensing using magnification maps calculated for random distributions of stars in the lens galaxy to study the accretion disk structure. They found that the observed microlensing magnifications are compatible with the temperature profile of the thin accretion disk model (Shakura & Sunyaev 1973). In the case of HE 0435−1223, Mosquera et al. obtained a Bayesian estimate for the half light disk radius in the range from 8 to 15 light-days. The most thoroughly studied case is, however, that of SBS 0909+532. The offset between the emission line and continuum ratios has been noticed in different works that extended the observational wavelength coverage of this object from the optical (Oscoz et al. 1997, Motta et al. 2002) to the UV (Mediavilla et al. 2005) and the IR (Mediavilla et al. 2011). Mediavilla et al. (2011) used this very large spectral coverage to obtain the offsets between the flux ratios corresponding to 14 emission lines and the underlying continua (see Figure 2), obtaining the dependence of microlensing magnification with wavelength. Using a Bayesian approach based in randomly placing a Gaussian source on microlensing magnification maps, they estimate the probability of reproducing the observed microlensing magnifications for different values of the size of the accretion disk and of the power law index () relating the disk sizes at different wavelengths (size $\propto \lambda^p$). They found values in the range of 4 to 8 light-days for the half-light radius, and of around 1 for the power law index, . The size inferred for the accretion disk is substantially greater than the one predicted from the intrinsic quasar flux and the standard thin disc model. This discrepancy has been also found by other authors (Pooley et al. 2007, Morgan et al. 2010, Blackburne et al. 2010). The discrepancies may be reduced by considering values of substantially larger than the one corresponding to the standard model, $p = 4/3$ (Poindexter et al. 2008, Morgan et al. 2010). However, the values of necessary to bring the different measurements of the size in agreement, $p \approx 2$, are very high as compared with the estimates of the different authors (Floyd et al. 2009, Morgan et al. 2010, Blackburne et al. 2010) and correspond to the limiting case where local energy radiation from accretion plays not role in the heating at a given radius (Gaskell 2008).

3.3. Extragalactic extinction laws

The effects of dust in the radiation must be corrected to interpret the observations of astrophysical sources. In particular, extinction effects are very important in a broad range of extragalactic problems, like the evolution of the stellar formation rate, the evolution of the stellar populations or the determination of cosmological parameters (see Mediavilla et al. 2005). Many of these studies involve the comparison of observations taken at different redshifts that should be corrected taking into account the possible evolution of dust properties. However, the standard method for obtaining extinction curves is based in the comparison of pairs of reddened and unreddened stars of identical spectral type (Massa et al. 1983). This limits the application of this method to the Local Group of Galaxies where high signal to-noise ratio (S/N) spectra of individual stars can be obtained.

As discussed above, the standard pair method can be extended to the extragalactic domain by using pairs of images of lensed quasars (Nadeau 1991). Many of the applications of this idea have been based in broad or narrow band photometry. Falco et al. (1999) were able to estimate 37 differential extinctions. Muñoz et al. (2004) estimated the extinction laws in two intermediate-redshift galaxies and found unusual extinction curves compared with the MW. Elíasdóttir et al. (2006) used theoretical analysis and simulations to study the effects of extinction in 10 intermediate redshift galaxies and found no evolution of the dust properties with redshift even though, as they point out, a larger sample of lenses would be needed to reach a robust conclusion. Finally, Mosquera et al. (2011) determine the extinction curve in the $z = 0.58$ lens galaxy of SDSS J1650+4251, and find that the 2175 bump is absent. These photometric determinations integrate in each filter both continuum and emission lines and can be affected by microlensing. On the contrary, approaches based in spectroscopy can separate the emission line and continuum flux ratios to avoid microlensing effects. This has been done in HE 0512-3329 by Wucknitz et al. (2003) and in SBS 0909+532 in a very large wavelength range covering from the optical (Oscoz et al. 1997, Motta et al. 2002) to the UV (Mediavilla et al. 2005) and the IR (Mediavilla et al. 2011). Using together all the data, Mediavilla et al. (2011) have obtained an extinction curve of quality and wavelength comparable to the determinations made for the Milky Way, finding that the best fitting extinction curve is similar to the LMC2 Supershell with a weaker 2175 feature and a steeper rise into the UV than that observed in the Milky Way.

3.4. The 2175 bump

A significant conclusion that can be extracted from the limited number of extragalactic extinction curves inferred from lensed quasars, is the variability of extinction curves and dust properties. This must be taken into account for correcting astrophysical and cosmological data. The use of a same extinction law to correct data taken from different environments is very doubtful, especially in the UV. This variability is also important to understand the astrophysics of the absorbers (Draine 2003). In particular, one of the most conspicuous features of extinction laws, the 2175 bump, has been detected in SBS 0909+532 (Motta et al. 2002), there is marginal evidences of it in HE0512-3329, (Wucknitz et al. 2003) and Q0957+561 (Goicoechea et al. 2005) but it seems to be absent in LBQS1009-0252 (Muñoz et al. 2004) and in SDSS J1650+4251 (Mosquera et al. 2011). There are a few evidences from other grounds (Eliasdottir 2009) of this significant feature whose origin (graphite, PAH, silicates, …) is not clear (Draine 2003, Wrickamasinge et al. 2005, Trimble 2007, Eliasdottir 2009) although there are strong evidences that the carrier of the 2175 bump was in place when the Universe was only 20% of its current age (Eliasdottir 2009).

4. Final Remarks

The almost 200 known gravitational lenses offer experimental prospects to the astronomers rarely available in astrophysics. Within the phenomenology of light deflection by galaxies, the study of chromaticity, and its fluctuations, induced by the fluctuations of the gravitational field as seen in color microlensing effects (Vakulik et al 2004) or by the inhomogeneous distribution of the interstellar medium, is a very useful tool to probe the distribution of matter in the lens galaxy, the unresolved structure of quasars and the evolution of dust properties. Statistical studies based on high quality gravitational lens spectroscopy will significantly extend our knowledge of galaxies and quasars.

5. References

Alcock, C., et al. 2000, ApJ, 542, 281

Belokurov, V., Evans, N. W., & Le Du, Y. 2004, MNRAS, 352, 233

Blackburne, J.A., Pooley, D., Rappaport, S., & Schechter, P.L. 2010, arXiv:1007.1665

Calchi Novati, S., et al. 2005, A&A, 443, 911

Draine, B.T. 2003, ARAA, 41, 241

Elıasdottir, A., Hjorth, J., Toft, S., Burud, I., & Paraficz, D. 2006, ApJSS, 166, 443

Elıasdottir, A., et al. 2009, ApJ, 697, 1725

Falco, E. E., et al. 1999, ApJ, 523, 617

Floyd, D.J.E., Bate, N.F., & Webster, R.L. 2009, MNRAS, 398, 233

Gaskell, C.M. 2008, Revista Mexicana de Astronomia y Astrofisica Conference Series, 32, 1

Goicoechea, L.J., Gil-Merino, R., & Ullán, A. 2005, MNRAS, 360, L60

Griest, K., & Thomas, C. L. 2005, MNRAS, 359, 464

de Jong, J. T. A., et al. 2006, A&A, 446, 855

Kochanek, C. S. 2004, ApJ, 605, 58

Kochanek, C.S., & Dalal, N. 2004, ApJ, 610, 69

Massa, D., Savage, B. D., & Fitzpatrick, E. L. 1983, ApJ, 266, 662

Mediavilla, E., Muñoz, J.A., Kochanek, C.S., Falco, E.E., Arribas, S., & Motta, V. 2005, ApJ, 619, 749

Mediavilla, E., et al. 2009, ApJ, 706, 1451

Mediavilla, E., et al. 2011, ApJ, 730, 16

Morgan, C. W., Kochanek, C. S., Dai, X., Morgan, N. D., & Falco, E. E. 2008, ApJ, 689, 755

Morgan, C.W., Kochanek, C.S., Morgan, N.D., & Falco, E.E. 2010, ApJ, 712, 1129

Mosquera, A.M., Muñoz, J.A., & Mediavilla, E. 2009, ApJ, 691, 1292

Mosquera, A.M., Muñoz, J.A., Mediavilla, E., & Kochanek, C.S. 2011, ApJ, 728, 145

Motta, V., et al. 2002, ApJ, 574, 719

Muñoz, J. A., Falco, E. E., Kochanek, C. S., McLeod, B. A., & Mediavilla, E. 2004, ApJ, 605, 614

Nadeau, D., Yee, H. K. C., Forrest, W. J., Garnett, J. D., Ninkov, Z., & Pipher, J. L. 1991, ApJ, 376, 430

Oscoz, A., Serra-Ricart, M., Mediavilla, E., Buitrago, J., & Goicoechea, L.J. 1997, ApJ Letters, 491, L7

Paczynski, B. 1986, ApJ, 304, 1

Poindexter, S., Morgan, N., & Kochanek, C.S. 2008, ApJ, 673, 34

Pooley, D., Blackburne, J.A., Rappaport, S., & Schechter, P.L. 2007, ApJ, 661, 19

Schild, R.E. 1996, ApJ, 464, 125

Schechter, P. L., & Wambsganss, J. 2002, ApJ, 580, 685

Schechter, P. L., & Wambsganss, J. 2004, Dark Matter in Galaxies, 220, 103

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Tisserand, P., et al. 2007, A&A, 469, 387

Trimble, V., Aschwanden, M.J., & Hansen, C.J. 2007, SSRv, 132, 1

Vanderriest, C. 1990, Gravitational Lensing, 360, 210

Vakulik, V. et al, 2004, Astronomy & Astrophysics, 420, 447

Wambsganss, J. 2006, Gravitational Lensing: Strong, Weak and Micro, Saas-Fee Advanced Courses, Volume 33. ISBN 978-3-540-30309-1. Springer-Verlag Berlin Heidelberg, 2006, p. 453, 453

Webster, R. L., Ferguson, A. M. N., Corrigan, R. T., & Irwin, M. J. 1991, AJ, 102, 1939

Witt, H. J., Mao, S., & Schechter, P. L. 1995, ApJ, 443, 18

Wickramasinghe, N.C., Wickramasinghe, J.T., & Mediavilla, E. 2005, ApSS, 298, 453

Wisotzki, L., Koehler, T., Kayser, R., & Reimers, D. 1993, A&A, 278, L15

Wisotzki, L., Koehler, T., Ikonomou, M., & Reimers, D. 1995, A&A, 297, L59

Wucknitz, O., Wisotzki, L., Lopez, S., & Gregg, M.D. 2003, A&A, 405, 445

Yonehara, A., Hirashita, H., & Richter, P. 2008, A&A, 478, 95

Xu, D.D., et al. 2009, MNRAS, 398, 1235

6. Figures

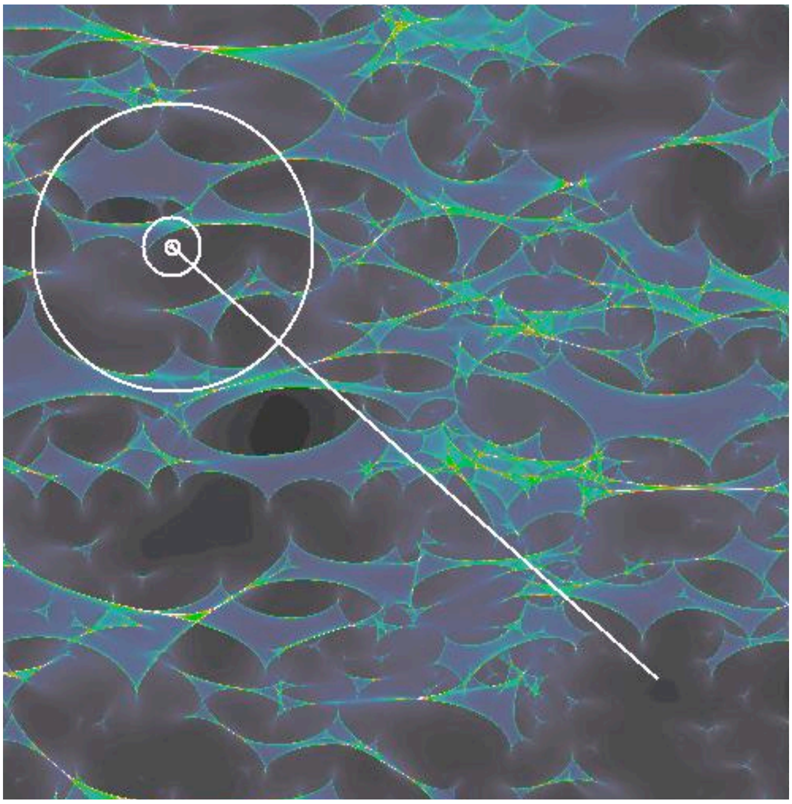

Figure1a – Magnification map showing the high gradients across caustic curves. The magnification of a source is computed integrating the area of the magnification map covered by the source weighted by the source intensity. Circles correspond to several sources of different sizes.

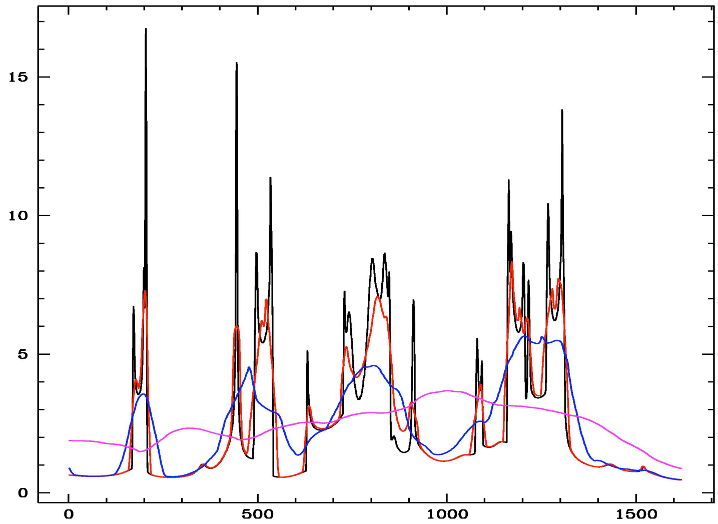

Figure 1b - Light curves corresponding to sources of different sizes (see Fig. 1a; violet > blue > red > black) moving along the track drawn in Fig.1a. The impact of microlensing is very high for the smaller source (black) neatly showing each caustic crossing but is considerably averaged out for the larger one (violet).

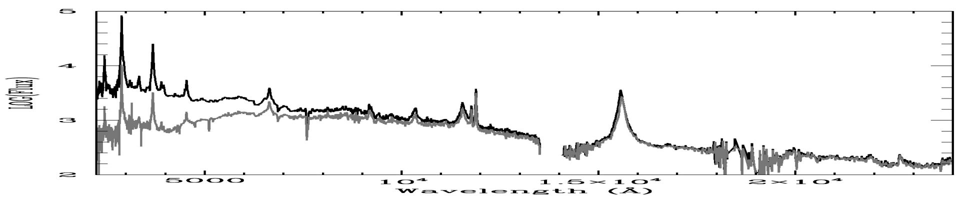

Figure 2 – Spectra, from the UV to the Near IR, of the two images of SBS 0909+532 (Mediavilla et al. 2011). Notice the strong extinction of the weaker component in the UV and the presence of emission lines that arise from regions of larger size than the continuum.