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Multiply–imaged Transient Events in Cluster Lenses

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Abstract: ARIES had a successful gravitational microlens project during 1998–2002. A similar monitor for Transient Events in galaxies at high redshift lensed by rich galaxy–clusters provides a challenging possibility with important cosmological implications. Rich galaxy–clusters at intermediate redshifts are powerful gravitational lenses which produce multiple images, in the shape of giant arcs of 5–20" extent, of distant background galaxies in their field. Weak lens shear of the background galaxy distribution can reliably trace the lens mass profile. Multiple images of supernovae or GRBs in the background galaxies can be recorded in a systematic monitor of the system. An unlensed high redshift supernova might not be observable, but when lensed by a galaxy-cluster, it will stand out because the point event brightens relative to the host. The color profile of a high redshift lensed point event will be much more reliable than an unlensed one due to much less host contamination. An estimate of the time delay enables observation of the full light curve of the subsequent images of the event. ARIES can have outside collaboration for multiband simultaneous lightcurves of other images. The measured time delay and position of images of the transient event provide better cosmological constraints including distance scale of the Universe. The Devasthal telescope can detect one or more events by monitoring half a dozen cluster fields over three years time.

1 Introduction

The gravitational deflection of light is a classical test of General Relativity, which was verified by the bending of starlight due to the Sun during the total solar eclipse of 1919. But a direct consequence of this phenomenon, the gravitational lensing became a serious field of astronomy only in 1979 with the discovery of the first multiply–imaged lens system, 0957+561 by Walsh, Carswell & Weymann (1979). Since then, it has become a powerful probe of the structure distributions at various scales, properties of individual lenses, as well as the underlying cosmology. Two important properties of lens which have become handy as an astronomical technique are (1) Multiple image formation in the "strong lens" regime and (2) A small but coherent distortion of the background sources called weak lens shear. A lensing event occurs when the gravitational field of an intervening massive body like a star, a galaxy or a cluster of galaxies deflects the light paths coming from a suitably aligned background source. This leads to a distortion of the position, size, shape and even intensity of the distant source. Typically, the observational signatures manifest as multiple images, with almost identical spectral characteristics as well as arcs and almost complete ring-like image morphologies created by the reshaping of an extended source such as a galaxy by the lensing action of a foreground deflector.

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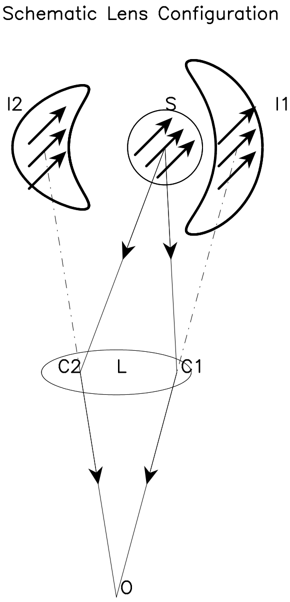

Figure 1: A schematics of gravitational lensing. A lens at L produces two images I1 and I2 of a distant background source S which the observer finds along directions towards C1 and C2 in the lens plane. the images are distorted, but the intrinsic properties denoted by the arrows in the source remain the same in the images.

The essentials of multiple image formation is illustrated in Fig. 1, where a distant source S is lensed by the compact object L resulting in the formation of two images I1 and I2. The shape or magnification of the images will be different; but their intrinsic properties like plane of polarization of a radio source at a specified scale or rotation curve of a lensed spiral galaxy will be mapped invariantly to the images as shown by the arrows in the source, subject to the effects introduced by the lens. Of course, there is a time delay introduced due to the different paths taken by the light rays forming the images.

2 Cluster lensing

In a paper describing one of the first realistic models of giant arc formation due to the lensing action of a massive cluster on a background galaxy in the system Abell 370 (Fort et al 1988, Lynds & Petrosian 1986), Narasimha & Chitre (1988) argued that a supernova explosion in the lensed galaxy could manifest in the multiple images forming the arc at different times and monitoring the events could turn out to be a powerful cosmological diagnostic. Supernovae have been detected in the field of cluster lenses since then. One supernova event was reported in a spiral galaxy at a redshift of 1.49 lensed by the massive cluster MACS J1149.6+2223 at a redshift of 0.54 (Kelly P.L. et al, 2015). We missed it narrowly, though we (PI: M. Pommier-Pandey) had observed the cluster with GMRT under the MACS cluster project just before the event. Why is this such an important probe?
A parameter describing the mutiple image forming capability of a galaxy or galaxy cluster is the

critical surface mass density $\frac{c^2}{4\pi G D_{eff}}$, where c is the speed of light, G is the gravitational constant and $D_{eff} = \frac{D_L D_{LS}}{D_S}$, the combination of distances to the lens and the source. If the surface mass density in the central region of the lens, projected on a plane perpendicular to its line of sight, is comparable to or above the critical value, we expect to observe arcs or multiple images or highly magnified images of background sources located almost along the line of sight to the lens. The value of the critical surface mass density decreases as D_{eff} increases and at a redshift of around 0.2, rich compact galaxy–clusters and massive galaxies can act as powerful lenses. At the higher end of redshift, the limit is by the faintness of images as well as the existence of a sufficient number of sources at very high redshifts.

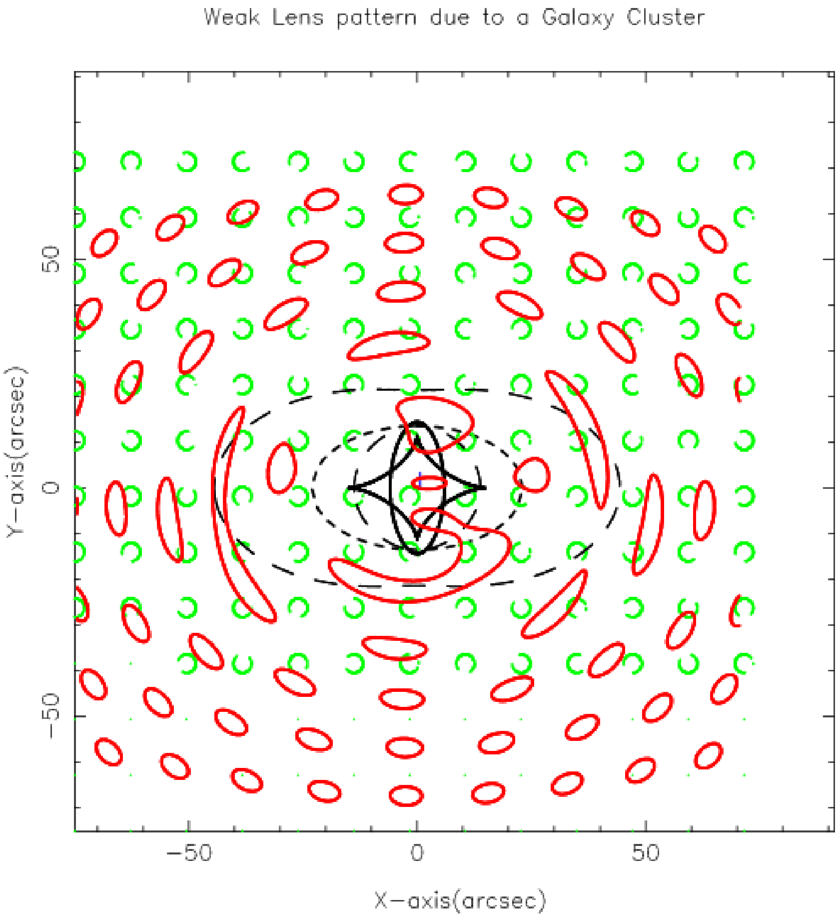

Figure 2: A simulation of lensing by a rich cluster of galaxies: The dotted black curve is a scale of the cluster mass distribution. The black solid lines are caustics in the source plane delineating the regions of image multiplicity and the long dashed black lines are the corresponding critical curves in the image plane. Close to these critical curves are the highly magnified giant arcs and multiple images while at far outside, the slightly distorted images, all in red. The corresponding background source galaxies are the green circles.

Galaxies and Galaxy–Clusters at intermediate redshifts (0.2–0.7) satisfy these conditions. Their projected surface mass density of $\sim$0.5 gm/cm^2 is sufficient for the formation of highly magnified images of background galaxies along the critical curves, which delineate the regions of multiple imaging. A schematics of the cluster lensing is displayed through a simulation in Fig. 2. The outer slightly distorted ellipses are the weakly lensed images of background galaxies (green circles) in the field. The coherent distortion of these galaxies can be used for reconstructing the density profile of the lensing cluster by lens inversion. But near the cluster centre, we see a few giant arcs and radial arcs, which are the highly magnified, and sometimes multiply imaged background galaxies, strategically located behind the cluster. Multiple image formation, in the shape of giant arcs of 5 to 20 arcseconds has been observed for a large number of clusters. Narasimha & Chitre (1988) argued that supernovae in arcs could provide a powerful probe to trace the full multi–band light curves of the transient events because they will repeat in the various images at various epochs due to time–delay effects, which could typically amount to months to years. There are a few other subtleties worth mentioning:

- Cluster lenses act as natural telescopes, producing magnification of even a factor of 100 in some cases. Consequently, objects difficult to detect or monitor otherwise can be observed at high redshifts.

- The surface brightness of the host galaxy remains unaltered due to lensing but its extent increases tangentially; however, the point transient event like supernova or GRB will continue to be a point in the images, but retain their temporal characteristics in the images.

- The color of a high redshift supernova could be severely affected by the host due to the relative fluxes. But when lensed, this contamination could become negligible.

Monitoring a few suitable cluster fields for transient events like Supernovae or GRBs offers many advantages. Here are a few illustrative numbers to substantiate the claim (discussed in the February 2015 meeting on Transient events organized at NCRA in the sidelines of the ASI meeting) :

A supernova of peak -17 B magnitude is 10–100 times fainter than the host galaxy, but occupies the *same* 'atmospheric seeing disk' as the host at a redshift of 1. But when it is lensed by a galaxy–cluster, the surface brightness of the host remains same but the length increases due to magnification. However, the Supernova, which is a point source has same size but flux increases and hence is easily detected. Due to the brightness contrast, subtraction of the flux of the host galaxy is easy and the derived color is more reliable. This is demonstrated in Fig. 3, where a galaxy cluster lenses a background galaxy, producing three images. There is a solid elongated diamond shaped black curve and another almost circular thick black curve centered on the cluster centre, depicting the tangential and radial caustic. Notice a small black circle straddling over these two curves, representing the lensed galaxy, which is imaged into a merging giant arc and a smaller arc. There is an almost invisible tiny circle in the source galaxy representing the supernova. But the images of the supernova appear as three distinct bright ellipses inside the black giant arc. The other colored curves represent images for systems at different redshifts and positions. Multiple giant arcs with characteristic breaks and morphology, with contrasting flux profiles have been observed in many cluster fields, notably the famous Abell 2218.

We might not have obtained the full light curve of the first image of the GRB or Supernova. But, due to our rough estimation of the time delay and position of the other images, we can direct the telescope towards the target at later times to obtain the full light curve of the supernova along with information in other wavelength bands from outside telescopes. (Naturally, we might not have the exact time delays). This could be a way the 3.6m ARIES telescope can have a collaboration with SKA or some Space X-ray instrument. The additional byproduct is an accurate measurement of time delay in this cluster lens. The measured time delay between the multiply–imaged Supernova and position of the images of the event provide better constraints on the mass of the cluster as well as distance scale of the Universe.

A rich cluster field will have half a dozen of extended images. A typical distant galaxy, with its increased star formation rate, will have more than one event in 30 years. A supernova can be detected within 30 days of explosion. Monitoring half a dozen cluster fields over two year time scale in two bands about five times a month, should enable us to detect one or more events with the Devasthal

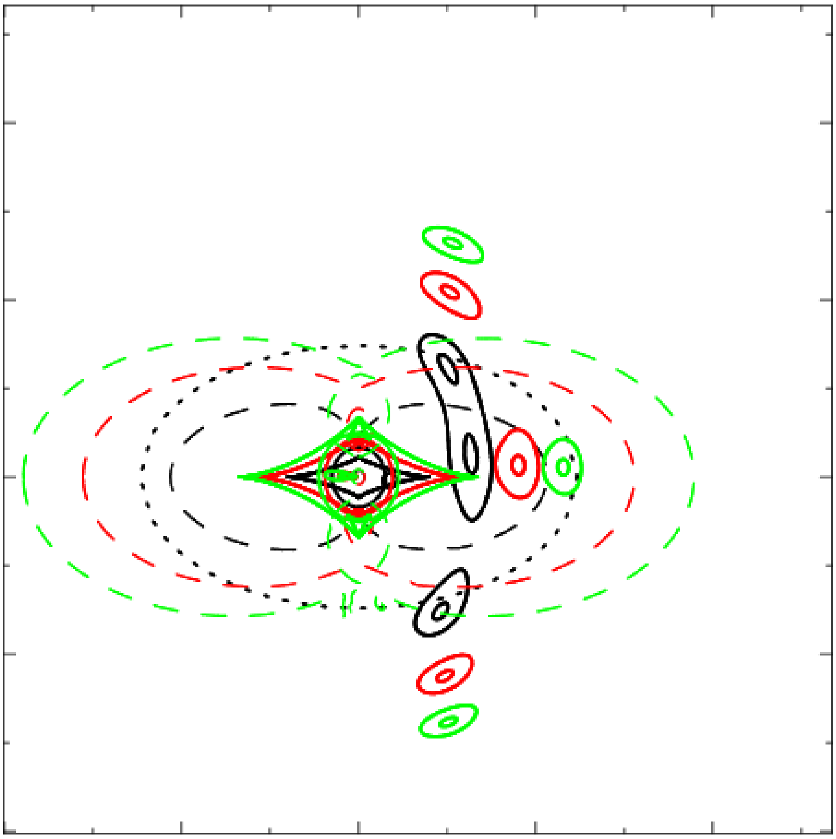

Figure 3: A simulation of multiply–imaged supernova lensed by a rich cluster of galaxies: The black solid lines represent caustics in the source plane delineating the regions of image multiplicity and the long dashed black lines correspond to the critical curves in the image plane. The dotted black curve is a scale of the cluster mass distribution. There is a small black circle straddling the black caustics, representing the background lensed galaxy, which has an almost invisible dot indicating the supernova. the images of the supernova are evident in the merging and isolated black giant arcs, which are the images of the galaxy. The red and green curves represent the same for a galaxy at higher and higher redshifts.

Optical Telescope, where we expect to do photometric calibration at 24 magnitude level (hopefully). If you trust the measured width and length of giant arcs and sizes of other field galaxies, it might be possible to estimate the magnification of the images and hence, the unlensed magnitude of the supernova. This could possibly be useful to extend the Supernova Cosmology projects to beyond a redshift of 3. Using strategically located rich galaxy clusters to search for Supernovae or gamma ray bursts at redshifts of five should be worth exploring.

3 Summary

- The galaxy–clusters at intermediate redshift (0.2–0.7) constitute powerful gravitational lenses that can form highly magnified multiple images of strategically located background galaxies.
- Narasimha & Chitre (1988) argued that a high redshift supernova in a galaxy lensed by a cluster could be a powerful diagnostic of the cluster, the high redshift supernova as well as the Cosmology.
- The full light curve and color profile of a supernova or GRB event can be obtained by planned

observations, following the detection of a supernova event well after the explosion, in some part of a multiply–imaged giant arc.

- One supernova event (the Refsdal supernova) was reported by Kelly et al (2015) in a spiral galaxy at a redshift of 1.49 lensed by the massive cluster MACS J1149.6+2223 at a redshift of 0.54, thereby demonstrating the feasibility of the project.
- The Devasthal telescope offers a bright prospect for high redshift supernova based Cosmology.

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