Marginal lensing by rich clusters of galaxies

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A marginal lens is barely capable of multiple imaging of a background object at a given redshift. This phenomenon of *marginal lensing*[1] becomes particularly important when sources situated behind rich galaxy-cluster at moderate redshifts ($z \gtrsim 0.2$) are imaged down to 25th magnitude or even fainter limits. Some of the signatures of marginally lensed configurations are: (a) background galaxies very near the line of sight through the cluster centre imaged into straight arcs, (b) point sources like quasars lensed into two images of equal brightness, and (c) many background galaxies in the field, all elongated almost normal to the major axis of the cluster. Detailed investigation of marginal lenses and the resultant image configurations turn out to be powerful probes of large scale geometry of Universe as well as mass distribution in the cluster. The recently observed lensing morphology in rich cluster of galaxies AC114 is employed to qualitatively illustrate some of the diagnostic methods.

GRAVITATIONAL lensing provides one of the powerful diagnostics of large-scale structure of the Universe at cosmological distances. Although observational gravitational lensing is a relatively young field, already there are some definitive indications about the large-scale structure of Universe gleaned from observations and detailed lens modelling. Thus, we can surmise that in clusters, mass follows the X-ray luminosity and optical number density of galaxies reasonably well outside the very central region. On the other hand, bulk of the mass in field galaxies is probably distributed in halos[2] with sizes of the order of 100 kpc and core radii of 10 to 30 kpc as against their luminosity which is mainly emanating from regions of less than a few tens of kpc. Lens galaxies located up to redshift, $z \lesssim 1$ have large-scale mass distribution, not very different from what could be inferred about the ones in our neighbourhood. Also, the time-delay measurements between images of the same background lensed source in systems like 0957+561 are suggestive of the Hubble constant being nearer to 50 rather than 100 km s^{-1} Mpc^{-1} (refs. 3, 4).

Formally lensing is a map from a two-dimensional surface (source plane) to another two-dimensional surface (image plane) governed by the three dimensional mass distribution of the cluster. A general lens has, therefore, extra degrees of freedom which cannot be uniquely determined from the present observations. However, the number of degrees of freedom of the system can be reduced vastly by making use of the following three properties:

1. Small scale inhomogeneous mass distribution in the lens does not affect positions but changes only the area magnification.
2. When objects at various redshifts are lensed by the same foreground object, the permitted profiles of large scale mass distribution in the lens are restricted.
3. Lenses and sources have many symmetries due to which the relevant properties of the configuration can be conveniently parametrized.

There exist a variety of lensed configurations, e.g. galaxies being lensed into arcs by foreground rich clusters of galaxies, where the observed special features can be effectively modelled in terms of known properties of nearby galaxies and clusters. As a result, when analysing a peculiar or special lensed morphology, we have the advantage of being able to use an incomplete or noisy observation-set and still obtain reliable information about the lens.

During the last couple of years some remarkable lens configurations have been observed mainly because it is now possible to get sensitive images of sources down to or even fainter than 27th magnitude with a few hours of exposure[5]. The estimated density of sources at that magnitude limit is of the order of a few hundred per square arc minute. Consequently, gravitational lens effects of *any object* which has lensing capability extending up to angular scales of a few tens of arc-seconds will be observable through either multiple images of part of some background source situated nearly along the line of sight to the deflecting object or extended images like rings or arcs. Further, because of the magnification of the sources due to lensing, a large number of objects which are otherwise too faint to be visible are being detected. As a result, the phenomenon of marginal lensing, where a background source is being barely multiply imaged but magnified substantially, has become an important method to study rich clusters of galaxies.

In this work we attempt to give qualitative discussion of lensing events due to rich clusters of galaxies, the role of marginal lensing and the use of this phenomenon to infer mass distribution in the cluster as well as possibly the geometry of Universe at large. We propose to use the rich cluster of galaxies, AC114 as a typical example. This is because, while signature of lensing has been already observed in this system[6], some of the predictions given here are testable in the near future.

It should be stressed that marginal lens does not necessarily mean any special lens; we are only concerned with a *typical* rich cluster of galaxy which is situated at large enough distance such that it can produce multiple images of some sources at even larger distances[10], and we assume that we have instruments capable of observing faint enough objects at large redshift. A galaxy or cluster of galaxies can generally produce multiple images of a background source near its line of sight if its projected surface mass density is above a critical limit

$$\Sigma_{cr} = \frac{c^2}{4\pi G D_{eff}},$$

where c is the velocity of light, G the gravitational constant and the distance measure,

$$D_{eff} = \frac{D_{ls} D_l}{D_s},$$

depends on the distance from the source to the observer, D_s, distance from the lens D_l, and the distance from the source to the lens D_{ls}. (Multiple imaging with smaller mass density is possible[7], but here we are concerned with certain global properties of the lens only.) It is evident that smaller mass density is sufficient for multiple imaging if the lens is far away, though the image separation will also become correspondingly smaller. A lens at a distance D_l which has mass density just sufficient to multiply image an extended source at D_s is designated a marginal lens for that distance. Marginal lens can produce image of large magnification provided the source is within certain angular distance. When the marginally lensed background source is an extended object like a galaxy, it is imaged into a shape of a straight arc. Kovner[1] analysed the local properties of marginal lenses at length and Narasimha and Chitre[8] studied their role in producing structures like straight arcs.

Galaxies in general do not serve as good marginal lenses for any distances, because it is difficult to separate the resultant image configuration from the lensing galaxy; moreover the cross-section for lensing is too low to detect any observable signature of lensing. However, rich clusters of galaxies at moderate redshifts are good candidates for this phenomenon. A cluster of velocity dispersion $\gtrsim 1000\,\mathrm{km\,s^{-1}}$ situated at redshift of $z \gtrsim 0.2$ can form multiple images of objects at redshift $z \gtrsim 0.5$ (these numbers should be taken only as illustrative) if the cluster has a large core radius (~ 500 kpc) and proportionately more mass, the cross-section for appreciable lensing action is of the order of arcminute^2. For the intrinsic parameters of such a lens and the relative position of the lens and the observer, there exists a narrow range of the redshifts of background sources and their positions at which they can be almost marginally lensed. It is fair to say that at a magnitude level of ~ 29 when almost any moderately distant rich cluster is being observed, the background source density is sufficient for at least one source in the field to be at the marginal distance.

Lensing action of AC114

AC114 is a well-studied rich cluster of galaxies at a redshift of $z = 0.31$ with a velocity dispersion of $\sim 1650\,\mathrm{km\,s^{-1}}$. Naturally, when Ellis and collaborators[6] took deep images down to 26th magnitude using HST and ground-based telescopes, many elongated structures, probably background galaxies at high redshifts, were detected. But the most exciting result was the presence of a pair of quasars of almost equal brightness (at $\sim$25th magnitude), separated by about 12″ situated close to the cluster centre. The redshift of these background objects is still not known, but from the analysis of the observed lensed sources, we can devise tests to infer the mass distribution in the cluster and possibly set weak limits on the geometry of Universe.

In order to study the lensing action of the cluster, we represent the smooth mass distribution within the cluster by a truncated King type profile, parametrized by the central mass density, core radius, ellipticity and the position angle of its major axis. But the details of the density profile are not important because unlike galaxies, the cluster lensing action is normally best studied within one core radius. However, we need to specify the core radius and ellipticity of the mass distribution, which we assume to be 400 kpc and 0.5 respectively. Our representation of the line of sight velocity dispersion σ_v is related to the mass of the lens by the expression[9],

$$GM = 9\sigma_v^2 r_{core}\sqrt{1-\varepsilon^2}\left[\ln(n+\sqrt{1+n^2}) - \frac{n}{\sqrt{1+n^2}}\right],$$

where n is the ratio of cut off radius to core radius of the cluster and ε, eccentricity of the cluster mass distribution. In principle, we can treat the mass distribution of each galaxy of the cluster individually, but the smooth density profile is adequate unless the galaxy is close enough to an image for the graininess to be important.

For $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$ and the lens parameters that we have used, the cluster acts as a marginal lens for objects at redshift of ~ 2. The critical curves in the source and image planes for this redshift

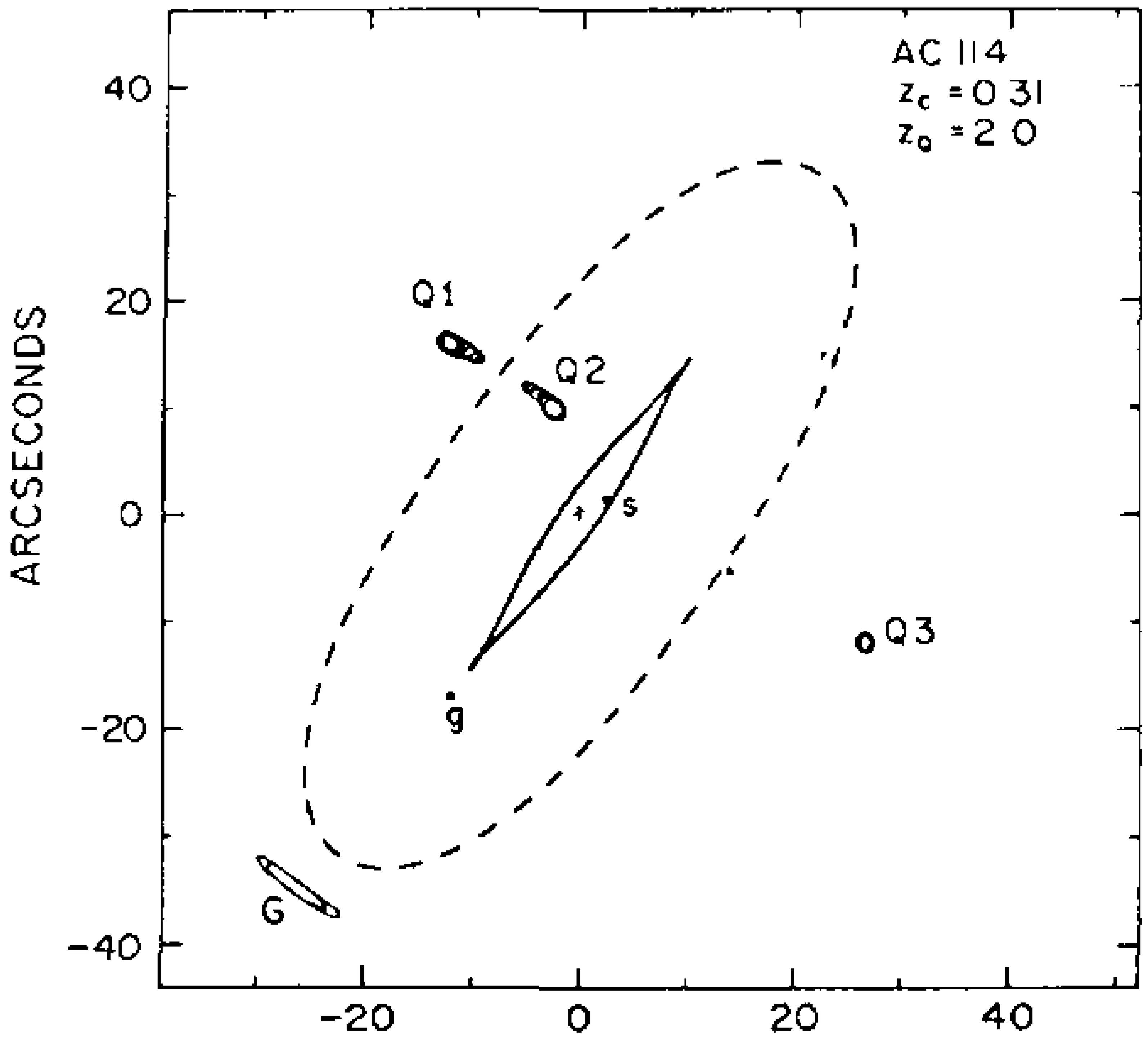

Figure 1. Model caustics and image configuration when a background quasar at redshift of 2 is lensed by the cluster AC114. The dashed curve is the critical curve in the image plane corresponding to the lip caustic (thick line) in the source plane when the mass distribution in the cluster is barely above the critical value for multiple imaging. The three images of quasar are denoted by Q1, Q2 and Q3 and the background source is the point, denoted by s, near the cluster centre nearly coincident on the caustic. The elongated object G is the image of a background galaxy, the source for which is the small circle outside the lip caustic, denoted by g.

and lens parameters are displayed is Figure 1. The main results applicable for the marginally lensed images are the following:

Three images of the background quasar, *s*, denoted by Q1, Q2 and Q3 lie nearly along a straight line, normal to the major axis of the cluster. Additional images due to local inhomogeneity are not ruled out, but the effects of graininess are discussed in the next section.

The main image pairs, Q1 and Q2 are magnified by almost the same amount. The brightness equality of these two images is a natural consequence of the source being located right near the fold critical curve. This results in two mirror images of each other, the magnification of each varying inversely as the distance of the image from the fold caustic.

Obviously, if this model is tenable, the third image should be observable at a magnitude of about 2 to 4 fainter than the two bright ones, though its position could differ by a few arcseconds from the location, Q3. When the redshift of the quasars is measured, it would either constrain the core radius of the cluster or the cosmological parameters adopted here.

Any other source at redshift *z* not too different from the marginal value situated near within a core radius of the cluster centre is appreciably magnified along the direction of the minor axis of the cluster. For example, the galaxy, denoted by *g*, is imaged into the elongated structure *G* at approximately 15″ from ,the cluster centre, which mimics the straight arcs observed in many of the rich clusters. Similar many elongated structures have been observed, the elongation being along the same direction as given in the figure. When the number of such sources is large, for each range of redshifts, one can compare the observed mean ratio of the length to width of the structures to the value expected from the model. This in general is a good test of the size of the cluster.

The definite prediction of the model is that there should be a third faint object having same redshift and spectral characteristics as the two bright images, lying nearly on the minor axis of the cluster within 20 to 40 arcseconds away from the cluster centre. Due to the effects of time delay and microlensing the similarity of the spectra might not be perfect; however, apart from some minor differences in the spectral characteristics, the object should be identifiable in relation to the two bright images of the quasar. [Richard Ellis has considered the possibility of three additional images in this system (private communication). While such a model cannot be ruled out, it will be *against marginal lensing* unless the additional images are produced by individual galaxies of the cluster, and consequently occur in pairs near the corresponding lens galaxy.]

Discussion

Local anisotropies in the cluster

The graininess due to individual galaxies or subclusters can modify the lens characteristics at small angular scales. In Figure 2, the influence of a cD galaxy located at the centre of the cluster is displayed. Note the distortion of the caustics and the consequent displacement of the image positions. In general, if the power at small scales is higher, the expected magnification of the images would be lower, and extended images show more pronounced curvature. This curvature is a signature of clumpiness in the cluster mass distribution. An idea of the importance of the lensing action of the central cD galaxy as against the large scale mass distribution of the parent cluster can be obtained, if we could observationally trace the caustic near the minor axis of the cluster.

Marginal lensing as cosmological diagnostics

It is possible to obtain the ratio $R=(D_{ls}/D_l)$ for an observed marginally lensed configuration, if the velocity dispersion and core radius of the cluster could be determined sufficiently accurately from independent observations. By studying a few rich clusters at moderate to

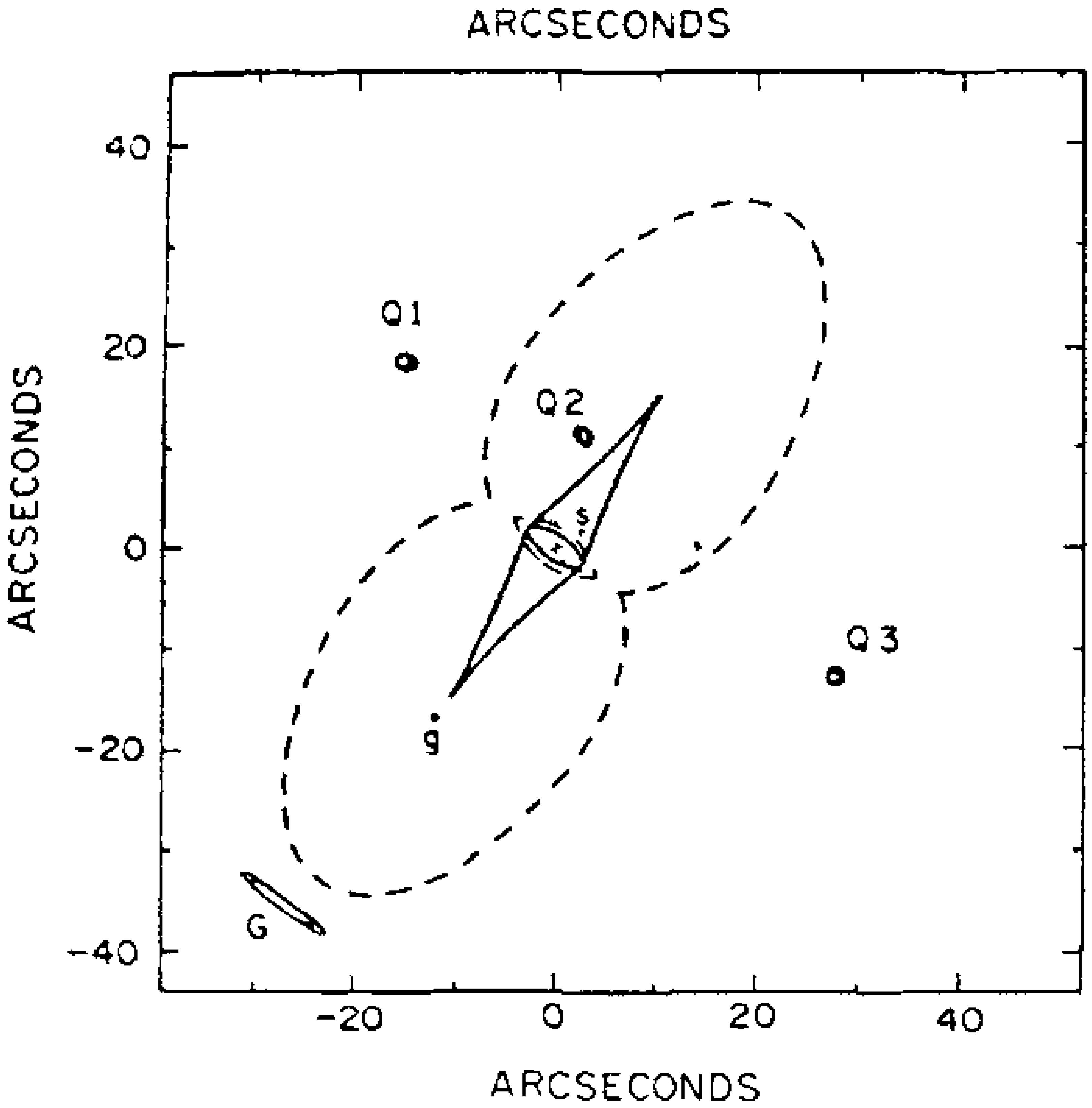

Figure 2. Caustics and image configuration for the cluster AC114 incorporating the lensing due to a cD galaxy of velocity dispersion 450 km s^{-1} and core radius of 10 kpc. The caustics and images are as in Figure 1.

large redshifts, we can find R as function of the source and lens redshifts. This information can be used to estimate the cosmological parameter q_0 and possibly test the large-scale geometry of the Universe. However, since the velocity dispersion and core radius are not known to the required degree of accuracy, the effectiveness of the method depends on the number of clusters studied. When the cluster redshift is upwards of 0.3, it is not easy to identify cluster membership of galaxies in the field and consequently direct redshift measurements of the objects in the field may not yield reliable velocity dispersion. However, X-ray observations could be useful in obtaining the cluster parameters if the resolution is better than about 5″.

Conclusions

We have outlined some of the main observational consequence of lensing due to rich clusters of galaxies at moderate redshifts and stressed the importance of marginal lensing as a powerful observational tool. A rich cluster should act as marginal lens for objects at certain redshift which is being governed by the cosmology and also the cluster parameters. From the observations of lens configurations and cluster properties like X-ray emission, it is possible to determine the cosmological parameters like q_0 or to infer the cluster mass distribution. We have studied the rich cluster of galaxies AC114 as a test case and made testable predictions. A systematic and complete observational study of clusters of galaxies having preassigned velocity dispersion, redshift range and X-ray emission characteristics will be important in understanding the large-scale properties of the Universe. Hopefully it will also help to determine the cosmological parameters from the lensing action of the clusters.

1. Kovner, I., *Astrophys. J.*, 1987, **321**, 686–705.
2. Narasimha, D. and Chitre, S M., *Astron. J.*, 1989, **97**, 327–335.
3. Lehar, J. *et al.*, *Astrophys. J.*, 1992, **384**, 453–466.
4. Narasimha, D., Subramanian, K. and Chitre, S. M., *Mon. Not. R. Astron. Soc.*, 1984, **210**, 79–88.
5. Fort, B., in *Gravitational Lenses*, Proceedings (eds Kayser, R. *et al*), Harnburg, 1991, pp. 267–278.
6. Smail, I., *et al.*, 1992. Durham preprint
7. Subramanian, K. and Cowling, S A., *Mon. Not. R. Astron. Soc*, 1986, **219**, 333–346.
8. Narasimha, D. and Chitre, S. M., *Astron. Astrophys.*, 1993 (in press).
9. Narasimha, D., Subramanian, K. and Chitre, S. M., *Mon. Not. R. Astron. Soc.*, 1982, **200**, 941–950.
10. Narayan, R., Blandford, R. and Nityananda, R., *Nature*, 1984, **310**, 112–115.

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