COSMOLOGICAL APPLICATIONS OF GRAVITATIONAL LENSING

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1. Introduction

It was recognized very early that the gravitational lens effect can be used as an efficient cosmological tool. Of the many researchers who foresaw the use of lensing, F. Zwicky and S. Refsdal should be explicitly mentioned. The perhaps most accurate predictions and foresights by these two authors are as follows: Zwicky estimated the probability that a distant object is multiply imaged to be about 1/400, and thus that the observation of this effect is "a certainty" [73] – his value, which was obtained by a very crude reasoning, is in fact very close to current estimates of the lensing probability of high-redshift QSOs. He predicted that the magnification caused by gravitational light deflection will allow a "deeper look" into the universe – in fact, the spectroscopy of very faint galaxies which are imaged into giant luminous arcs have yielded spectral information which would be very difficult to obtain without these 'natural telescopes'. And third, Zwicky saw that gravitational lenses may be used to determine the mass of distant extragalactic objects[72] – in fact, the mass determination of clusters masses from giant luminous arcs is as least as accurate as other methods, but does not rely on special assumptions (like spherical symmetry, virial or thermal equilibrium) inherent in other methods, and the determination of the mass within the inner 0.9 arcseconds of the lensing galaxy in the quadruple QSO 2237+0305 to within 2% [52] is the most accurate extragalactic mass determination known. Refsdal predicted the use of gravitational lenses for determining cosmological parameters and for testing cosmological theories [48][49] – we shall return to these issues below.

The discovery of the first gravitational lens in 1979 [68] marked the begin of 'modern' gravitational lens research. During the past 15 years this field has grown at an ever increasing rate, with about 13 known multiply imaged

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QSOs, 5 ring-like radio sources ('Einstein rings'), and a large number of arcs and arclets known today, and more than 1000 publications on that subject. Here I will describe some recent developments in the application of lensing for cosmology; for a more complete overview of the field, the reader is referred to our monograph [58], three recent review articles [8, 20, 50], and the proceedings of the most recent gravitational lens conference [65].

2. An update on H_0 through lensing

To determine the Hubble constant from a gravitational lens system, the time delay Δt between two (or more) images must be measured,

$$\Delta t = F/H_0, \tag{1}$$

where F is a dimensionless function which depends on the observed configuration of the QSO images, the redshift of source and lens, the cosmological parameters Ω (and λ), and, most crucially, on the mass model for the lens. Note that (1) can be inferred on dimensional grounds – the time delay is the only dimensional observable. Hence, the determination of H_0 requires two steps, the measurement of Δt from the varying flux of the QSO images and the construction of a 'correct' lens model. Both of these steps are much more difficult than anticipated originally.

The first double QSO 0957+561 has been monitored in the optical and radio bands since its discovery (i.e., for nearly 15 years); however, no generally accepted value for Δt has emerged. The analysis of the optical [55, 67] and radio [33] data by different statistical methods [47, 45] yielded no generally accepted results, with $\Delta t \sim 410$ or 540 days being preferred values – but at most one of those can be correct. Hence, the issue is currently not decided, despite the huge observational effort. There are clear signs of microlensing in at least one of the images.

Even if Δt for this system is eventually measured, the determination of H_0 will be highly uncertain, due to the complexity of the lens, which consists of a giant elliptical galaxy, embedded in a cluster at $z = 0.36$, with an additional concentration of galaxies close to the line-of-sight at $z \sim 0.5$. Certainly, the number of unknowns in a realistic lens model is larger than the (already large) number of observational constraints which come mainly from detailed VLBI imaging. If the lens indeed produces an arc [7, 16], earlier detailed lens models [19, 27] become insufficient, and this system will be unsuitable for the determination of H_0.

The system 0218+35.7 [43] is almost certainly the best lens system known to determine H_0; it consists of two compact components separated by 0.3 arcseconds and a radio ring. The small image separation suggests that the lens is a single (spiral) galaxy, and the Einstein ring will allow the construction of a detailed lens model, once it is properly imaged and resolved in width, and the compact components are variable. In fact, from polarized flux variations, a preliminary value of $\Delta t \sim 15$ days is suggested (I. Browne, P. Wilkinson, D. Walsh, private communication). Unfortunately, the source redshift in this system is still unknown.

In conclusion, H_0 is not yet determined from gravitational lensing, but reasonable estimates from the two systems mentioned lie in the range between 30 and 80 km/s/Mpc. Though this looks not like a very impressive achievement, the agreement with the values obtained by other (local) values provides a strong consistency check on our cosmological model, and strongly supports the cosmological interpretation of QSO redshifts. Furthermore, the estimates will improve and yield a single-step determination of H_0 on a truly cosmic scale, i.e., independent of local peculiar velocities and the distance ladder.

3. Lensing statistics, the cosmological constant, and galaxy merging

In recent years, several gravitational lens surveys have been performed in the optical [64, 71, 15, 37] and radio [10, 44] wavebands. In addition to finding new gravitational lens systems, these surveys can be analyzed statistically and compared with theoretical expectations. The results from such analyses [30, 38] can be summarized as follows: the frequency of multiple images in the existing surveys, and their distribution in redshift and apparent magnitude is fully compatible with standard assumptions on the cosmological model parameters, the commonly used parameters in the Schechter luminosity function for galaxies, the Tully-Fischer-Faber-Jackson relation, and the QSO luminosity function. The agreement of the lensing statistics with models does not significantly improve if the standard values for the parameters are allowed to vary [30]. Constant mass-to-light ratio models for early-type galaxies can be ruled out [38], since they would be in conflict with the observed lensing rate and image splitting, but these galaxies must have a dark (isothermal) halo. Moreover, the cosmological constant can be constrained to be ≤ 0.7, otherwise too many multiple images would be produced (a way to avoid this conclusion is obscuration in the lens galaxies with redshift above ~ 0.5 [22]). Also, there is not much room for compact 'dark matter' with $M \geq 10^{11} M_{\odot}$, since these objects would also from multiple images (from the fact that in more than half the lens systems, the lens is seen and thus not 'dark', one concludes that the mass density of compact dark objects in the relevant mass range cannot exceed that of galaxies). Lensing statistics can also be used to probe galaxy evolution and merging scenarios [36, 53], with the result that no-evolution models are statistically preferred; mild evolution cannot be ruled out, but strong merging scenarios are incompatible with the existing data.

One caveat should be kept in mind about these studies: all optical lens surveys have taken their target QSOs from existing catalogs, which do in no sense form unbiased samples. Existing QSO catalogs may be biased against multiply imaged QSO, though this effect is probably small [28]. However, if there exists a class of very red QSOs, and if the reddening is due to dust in *intervening* material, the results from the statistical interpretation of optical lens surveys may yield misleading results. The highly reddened quadruple QSO 0414+0534 [32] may provide a cornerstone for this important question, i.e., whether the reddening occurs in the lensing galaxy. Radio lens surveys are of course largely unaffected by this effect, but are hampered by the success rate of optical identification of source and lens.

The future of lensing statistics looks particularly bright, since the Sloan Digital Sky Survey will most likely find several hundred lens candidate systems, all detected with the same instrument, so that the selection function (which enters the lensing statistics in a significant way) can be well understood.

4. The size of Lyα clouds

The Lyα forest, seen in all high-redshift QSOs, is believed to be caused by intervening photoionized 'clouds'. The size of these clouds can be probed by multiply imaged QSOs or close QSO pairs, by studying the cross-correlation of the spectra of both QSO images: if most absoption lines are found in both spectra, and if these lines have comparable equivalent width, the size of the clouds must be significantly larger than the separation of the two light beams at the redshift of the cloud. A recent summary of this technique is found in [63], from which the following results are quoted: The double QSO UM673 shows a strongly correlated absorption spectrum, and only two (high S/N) lines are found in image A which do not occur in image B. If these two lines are indeed Lyα lines, the size of the clouds is estimated to be $12 \leq R/$ kpc ≤ 160, whereas if they are a MgII doublet, then $R \geq 23$kpc. The absorption spectrum of the recently discovered lens candidate system HE1104−1805 yields a preliminary lower limit on the cloud size of $R \geq$ 50kpc, whereas the QSO pair UM 680/681 yields $R \leq 750$kpc. As reported by Bechtold (this volume), the QSO pair 1343+266 yields an estimate for the size of the clouds of $R \sim 90$kpc.

5. Bounds on dark compact matter

Gravitational lensing is particularly suited to detect, or put upper limits on the density of compact objects in the universe. There are mainly two effects of gravitational light deflection which can be used for this purpose: multiple imaging and magnification (for a recent summary of limits on baryonic dark matter, see [12]). With current VLBI techniques, image separations down to a few tenths of a milliarcsecond can be probed for multiple images, corresponding to about $10^5 M_\odot$ [46]. Hence, imaging surveys with the VLBA, MERLIN, and the VLA can rule out a significant cosmological density of compact dark objects with masses larger than this value. If gamma-ray bursts are at cosmological distances, they can also be multiply imaged; though the image splitting cannot be observed, the time delay between different images will cause a repeating of the burst, separated by that time delay. Given that the shortest rise time of the bursts is about one millisecond, one can discover by this means objects with mass in excess of $10^3 M_\odot$. For smaller mass objects, the magnification must be used. Following the suggestions in [11], upper limits on the density of compact objects with $10^{-3} \leq M/M_\odot \leq 10^2$ have been obtained, by investigating the statistics of line-to-continuum flux ratios in QSOs [17] and upper limits on the variability of QSOs caused by these 'microlenses' [56]. The first of these methods is based on the assumption that the continuum emitting region is sufficiently small to be magnified by these lenses, whereas the broad line region is too large to be affected, whereas the second method relies on the assumption that the relative alignement of source, lens and observer must change in time due to peculiar velocities of all three members.

The limits one gets from these methods are interesting, e.g., $\Omega_c \leq 0.4$ in the mass range $10^7 \leq M/M_\odot \leq 10^9$ [26], and $\Omega_c \leq 0.2$ for $10^{-3} \leq M/M_\odot \leq 10^2$, and further significant tightening of these bounds will become available soon.

6. Arcs in clusters: $\Omega_0 \not\ll 1$ and cluster core radii

A recently completed survey for arcs in X-ray selected clusters of galaxies (Gioia, this volume) has shown that they occur at a fairly high rate. Theoretical expectations of arc statistics from simple (e.g., spherical or slightly elliptical) lens models [70] fall short by a huge factor. However, the predictions of arc statistics from simple models severely underestimate the true rate of occurrence [6], if compared with realistic mass distributions of clusters (obtained from a CDM simulation). The basic reason is that these numerically generated clusters, in accordance with observational results, show much more asymmetry and substructure than 'simple' model can account for, and that the 'central' surface mass density in such asymmetric clusters need not exceed the critical surface mass density [58] to produce arcs, in contrast to symmetric models. Hence, the large number of arcs in a complete sample of clusters provides strong evidence for clusters being unrelaxed and thus young (although the individual galaxies in the cluster generate an 'asymmetric' mass profile, the corresponding small-scale graininess appears to be insufficient to explain the large frequency of arc formation). This in turn implies that structure formation is still going on, i.e., that Ω_0 cannot be very much smaller than unity [51, 2].

In addition to the determination of the cluster mass, arcs can be used to constrain the mass profile in clusters (see also next section). In particular, the core radius of clusters as estimated from detailed lens models (e.g. [39]) is significantly smaller than the core radii as determined from X-ray observations of clusters, thus providing us with an interesting and potentially important discrepancy (e.g., [40, 34, 35]). Detailed observations of the clusters A370 [31] and MS2137−23 [39] yield stringent constraints on the core radius of the clusters, the ellipticity and orientation of the dark mass distribution; the corresponding lens models obtain their credibility from predicting multiple images where there are actually seen.

7. Cluster lens reconstruction

The perhaps 'hottest' topic in gravitational lensing today is the determination of the (surface) mass density of clusters from the image distortions they apply on distant faint galaxies [66]. The fundamental relation for this inversion was obtained in [25]:

$$\kappa(\vec{\theta}) = \frac{1}{\pi} \int_{R^2} d^2\theta' \, D(\vec{\theta} - \vec{\theta}') \, \gamma(\vec{\theta}'), \tag{2}$$

where κ is the (normalized) surface mass density (using the notation of [58]), γ is the shear, which describes the tidal effects of light deflection, and D is a known (and simple) kernel. Hence, if γ can be determined from the observed image distortions, then the surface mass density can be reconstructed. The basic assumption of this technique is that the intrinsic orientations of the faint galaxies are distributed randomly. First attempts to apply (2) to observational data [18, 62] are promising; since the accuracy of this method depends on the observable density of faint background objects, new observations by the Hubble Space Telescope will allow great progress to be made very soon.

It should be noted that the shear γ is not an observable [59], but the only observable from image distortions is a combination of γ and κ. Dispite of this difficulty, the inversion equation (2) can be applied, with γ being determined iteratively, as demonstrated in [60]. There exists a second problem with (2), namely that (2) is exact only if the integral is extended over the whole lens plane, whereas observational data will be confined to a (small) region determined by the size of the CCD. Using a differential relation between κ and γ, derived in [24], I have obtained an inversion equation which is exact for data given only on a finite region in the lens plane [57]. This modification of the inversion technique can yield quite substantial changes in the predicted surface mass density.

8. Cosmological coherent weak distortions and arcmin-scale QSO-galaxy associations: The power spectrum and the bias factor

Mass distributions less compact and more massive than clusters can lead to weak lensing effects, two of which should be mentioned here. Weak distortion of faint galaxy images caused by light deflection of the large scale mass distribution may be detectable [9, 23]. The two-point correlation function of the image ellipticities depends on the redshift distribution of the faint galaxies and on the power spectrum $P(k)$ of the density fluctuations. Hence, if this correlation function could be measured, one would have an integral constraint on $P(k)$, on the scales of about one degree. The rms image polarization predicted from a CDM model are about 3%. A pilot project [41] has recently yielded an upper limit of 5% image polarizations. More important than this number is the fact that such weak effects can now be measured. In a series of papers, it was recently shown that there is a statistically significant correlation between high-redshift radio QSOs and Lick galaxies [21, 3], IRAS galaxies [4] and X-ray photons from the ROSAT All Sky Survey [5]. The interpretation of these correlations as lensing by the large scale structure with which the galaxies are associated remains to be verified; as shown in [1], this interpretation yields for the two-point correlation function of high-redshift QSOs and galaxies

$$\xi(\theta) = (\alpha - 1)b \int dk\, P(k) \int dz\, G(k, z, \theta), \tag{3}$$

where α is the effective local slope of the QSO source counts, b the bias factor, and G depends on the redshift distribution of QSOs and the galaxies in a flux limited sample. The data used in the above quoted papers are not sufficient for measuring $\xi(\theta)$, but an analysis with a somewhat deeper galaxy catalog will enable us to measure ξ and thus to check the lensing interpretation of these correlations. In addition, with sufficient data, the power spectrum and the bias factor can be tested with weak lensing. Note that there are also indications for an overdensity of high-redshift QSO around Zwicky clusters [54, 61], which are not easily explained quantitatively by a cluster lensing model.

9. Final remarks

Due to the shortness of space, this review has to be selective; I have not discussed several very interesting developments in the field. For example, the search for microlensing in our galaxy has been much more successful than has been anticipated only one year ago, though it may turn out that the results from these searches tell us much more about stellar variability and the structure of the inner part of our galaxy than over cosmic dark matter. The constraints provided by the 'missing odd image' on the core size of lensing galaxies has also not been mentioned.

From the discussion here it is evident that gravitational lensing has developped from an 'exotic' subject to a quantitative tool in observational cosmology within the last few years. It provides the strongest constraints on the cosmological constant [13, 29] and (still) promises a way to determine H_0 (but is nearly blind with respect to q_0). Numerical simulations of the mass distribution in the universe soon will cover sufficiently dynamic range that they can be tested with respect to their predictions about multiple imaging of QSOs and weak image distortions; first results [14, 69] rule out standard CDM models, in agreement with analytical estimates [42]. The determination of the mass distribution in clusters through weak distortions has just begun to be explored; if one recalls that a deep HST image contains well in excess of 10^6 faint galaxy images per square degree, it becomes clear that this method will probably yield more robust results than any other method known. This in fact should not come as a surprise – the gravitational lensing effect depends only on gravity, which we think we understand very well, and not on more complicated and uncertain physical processes. Probably this simple but important thought led Zwicky, Refsdal, and others to their visionary foresights, which have turned out to be remarkable precise.

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