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Millennium Essay

The Future of Gravitational Optics[1]

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ABSTRACT. In this speculative, millennial essay, I try to anticipate what sort of novel gravitational optics investigations might be undertaken after it becomes possible to map and monitor roughly 10^{12} sources (of which 10^9 may be usefully variable) comprehensively throughout electromagnetic and other spectra over the whole sky. Existing techniques suffice to produce three-dimensional maps of the dark matter distribution of the accessible universe, to explore black hole spacetimes, and to magnify images of the first luminous sources, terrestrial planets, and compact objects.

1. THE PAST MILLENNIUM

This has been a good millennium for the study of gravitational optics. The foundations of the subject were set by the scholastics, Grosseteste, Bacon, and Theodoric, in the 12th and 13th centuries with their studies of rainbows and mirages. Four centuries later, Newton used Galilean kinematics to formulate his laws of motion and gravitation and develop his corpuscular theory of light using the laws of refraction, as previously elucidated by Snell and Descartes. Meanwhile, Fermat put forward the principle of least time, which made the connection between optics and dynamics that was cemented though the remarkable insights of Euler, Lagrange, and Hamilton, culminating in the development of quantum mechanics in the 20th century. Independent of these formal developments, Michell, Laplace, Soldner, and others quantified the magnitude of the deflection of light by gravitational fields according to Newton's theories, although their answer had to be doubled to allow for space curvature after Einstein perfected his general theory of relativity.

Observational progress had to wait until the last quarter of the 20th century. (It is impressive how much that we now observe in detail was anticipated, notably by Zwicky, Refsdal, Gunn, and Paczyński.) Following the first report of a strong (multiple-imaging) gravitational lens by Walsh, Carswell, & Weymann (1979), we have subsequently found cluster arcs (Soucail et al. 1987), weak lensing in clusters (Tyson, Valdes, & Wenk 1990), galaxies (Brainerd, Blandford, & Smail 1996), and the field (van Waerbeke et al. 2000), as well as microlensing (Irwin et al. 1989). These observations have had a big impact on cosmology and have already been used to estimate the size and shape of the universe, as tracers of dark matter, and as natural telescopes.

It is therefore with some optimism that the gravitational optics community can face the present millennium. What can we expect as we observe this splendid optical bench from our (presumably unprivileged) vantage point in spacetime? In this essay, I would like to take the long view and imagine that, one day, the whole universe within our past light cone will be comprehensively monitored throughout the electromagnetic and other spectra and that the exabytes of data that are produced will be automatically stored and searched.

2. COSMOLOGICAL SOURCES

From the deep imaging of the Hubble Deep Fields, it is apparent that Eddington was correct and that there are $\sim 10^{11}$ optical IR sources on the sky to ~30 mag, roughly 2″ apart on average. It is likely (and I shall assume) that most of these are protogalactic subcomponents with $z \sim 1$–3, although this has not yet been demonstrated. We will surely count these sources to fainter magnitudes and image overlapping galaxies so as to account for the brightness of the sky in essentially all bands in which the universe is transparent to roughly milliarcsecond resolution so as to provide a background of $\sim 10^{12}$ matchable sources for performing gravitational lensing investigations. (The fluctuating cosmic microwave background provides a similar source, but it is unlikely to have observable structure on angular scales that will be seen by any but the largest lenses.)

Roughly 10^7 galaxies have bright enough nuclei to be called quasars, and there are $\sim 10^8$ X-ray sources and $\sim 10^{10}$ compact radio sources (Kellermann & Richards 2001). In round numbers, I estimate that there are $\sim 10^9$ continuously varying, compact sources that will be monitored. Explosive sources are also interesting. Whole-sky searches to $z \sim 3$ should yield a supernova rate of $\sim 3\ \mathrm{s}^{-1}$ unless they are mostly obscured (Porciani & Madau 2000). Gamma-ray bursts (GRBs) will surely be traced to the faint end of their luminosity function at cosmological distances suggesting rates at least as large as $\sim 10^{-3}\ \mathrm{s}^{-1}$

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[1] This Essay is one of a series of invited contributions that will appear in the *PASP* throughout the years 2000 and 2001 to mark the new millennium. (Eds.)

(Blandford & Helfand 1999). (GRBs may also offer the opportunity to observe lensing effects associated with neutrinos and gravitational radiation.) For these purposes, afterglows are similar to supernovae.

3. GALAXY LENSES

A good way to think about the type of images that can form is to imagine a pencil of rays propagating backward in time from Earth (in the scholastically approved manner), past lensing galaxies and other masses and focusing on caustic surfaces. Sources located on rays between the first and second foci will form inverted images at Earth and be accompanied by at least two positive-parity images formed by different rays (unless there is obscuration) (Schneider, Ehlers, & Falco 1992). The comoving volume occupied by these putative sources, which I will call the lensing volume, is a measure of the number of observable instances of multiple imaging to be found. Double and quad image configurations are usually seen. The latter are rarer per source but are overrepresented in existing observations because they are more easily recognized and because they are strongly magnified. Most lenses are elliptical, on account of their greater central concentration and the denser environments in which they are found (Kochanek et al. 2000). Additional mass along the line of sight can also influence the imaging in a manner that will be quantifiable on an individual basis. Most galaxy lenses turn out to have $0.5 \lesssim z \lesssim 1$, and there are $\sim 10^9$ of them. If we imagine a typical lens with Einstein radius $\sim 1''$, then the lensing volume to $z \sim 3$ is roughly 1 Mpc^3 per lens. The total lensing volume containing strongly lensed sources is ~ 1 Gpc^3, roughly 1/1000 of the total comoving volume out to $z \sim 3$. This is consistent with the observed lensing probability per distant source ~ 0.001 and leads to an estimate of roughly one lensed source per lensing galaxy on average.

These considerations lead to an estimate of $\sim 10^9$ observable instances of gravitational lensing, although some of these will be hard to see against the light of the lensing galaxies. Point sources that lie close enough to caustics will create pairs of images that are linearly magnified along their lines of separation. It should be possible to identify them efficiently on spectral grounds. The lensing volume per lens with magnification greater than A is $\sim A^{-2}$ Mpc^3, and the most magnified sources of this type should have $A \sim 3 \times 10^4$, provided that they have detectable structure on a scale of $\sim 3A^{-1}$ kpc in order to remain unresolved by the gravitational lens. If one in 1000 of these sources is a variable active galactic nucleus, then the greatest intrinsic magnification in a variable source should be $A \sim 10^3$. Multiply imaged supernovae (GRBs) should occur every few minutes (weeks) and the brightest supernova (GRB) over a millennium should have $A \sim 10^4$ (10^2).

More interesting are the cusp lines that run along the caustic surfaces. Sources within and close to these cusps form bright, colinear triples in which the central image should have a flux equal to the sum of the fluxes from the other two images. The lensing volume, where the weakest of the three images has magnification $\gtrsim A$, can be estimated to be $\sim A^{-5/2}$ Mpc^3. The brightest galaxy cusps should have magnifications $A \sim 10^3$ if the sources are compact enough.

The next most prevalent catastrophe is known as the hyperbolic umbilic, and this has a three-dimensional caustic surface (Petters, Levine, & Wambsganss 2001). There are two of these associated with every elliptical lens possessing a finite core. They can form four image patterns looking like normal quads, but all four images lie on one side of the lens center. (The order in which these images varies differs from that found in regular quads, so they are distinguishable.) They are likely to be superposed on the lens galaxy and so are best sought using radio VLBI. Hyperbolic quads are very sensitive to the shape of the galaxy potential but are strongly magnified. If, as a calculation of a plausible galaxy model suggests is the case, the relevant lensing volume for forming them is ~ 0.01 Mpc^3 per lens, then there should be $\sim 10^4$ hyperbolic quad radio sources on the sky.

A second four-image, three-dimensional catastrophe is the swallowtail. This can occur if the galaxies form a close binary pair. Four roughly colinear images with alternating parity are formed, although there should be at least one other image in the vicinity. Groups and clusters are the best places to look for swallowtails, and there could be thousands of examples, which, if analyzed, would provide excellent probes of the galaxy potential on large scales.

The final three-dimensional, generic catastrophe is the elliptical umbilic. In its most likely manifestation, this involves three negative-parity images surrounding a positive-parity image, although there should be at least two additional, observable images in the vicinity. They are most likely to be located inside a triangle formed by three lensing galaxies with appropriate separations (Rusin et al. 2001). Although triple galaxies are less common than double galaxies, the lensing volume per galaxy within which a source will form a recognizable elliptic umbilic is larger, and these may outnumber swallowtails.

4. CLUSTERS AND COMPACT GROUPS

Clusters and groups influence lensing in two separate ways. They can magnify sources already lensed by galaxies, making them more common and easier to observe, and they can act as lenses in their own right. Of course, all clusters and groups can multiple-image through their brightest galaxies. Although the groups probably dominate the total lensing volume, the cluster lenses will continue to be of special interest because it is possible to map them with more confidence and precision. In round numbers, there are $\sim 10^5$ multiply imaging clusters, each with a lensing volume of ~ 100 Mpc^3. This implies that the probability of a distant source being multiply imaged by a cluster is $\sim 10^{-5}$. Cluster-induced caustics are capable of very large magnification (Blandford & Hogg 1996), and future space-borne interferometers should be capable of resolving individual bright stars, magnified 10^6 times as they cross the caustic curve.

Our observations need not be passive. Typical sources are likely move up to a parsec per millennium. This is enough for us to observe secular changes in the most strongly magnified sources and envisage more elaborate experiments. For example, suppose that we launch an array of robotic telescopes and use three of them to measure the velocity of a caustic sheet (formed by a bright source) as it passes Earth; a fourth telescope could be made to “surf” the wave and observe the source with considerable magnification for a long time.

5. WEAK LENSING TOMOGRAPHY

Weak lensing studies are, necessarily, statistical in character. However, when $\sim 10^{10}$ image shapes are measured over the sky, then it should be possible use them to map the dark matter distribution, assuming that we can determine their redshifts statistically (Tyson 2000). A typical, individual potential fluctuation on a nonlinear scale length of ∼30 Mpc creates a shear of $\sim 10^{-3}$. There will be roughly 100 of these regions along a line of sight whose effects add stochastically giving a typical total shear of $\sim 10^{-2}$. Using the $\sim 10^6$ sources behind each of these regions, it should be possible to measure the approximate shapes of their individual potential wells. Measurements on larger scales should have slightly larger signal-to-noise ratio. (A much greater number of source shapes is necessary to map typical regions of space as opposed to the much smaller number that already suffices to map large fluctuations such as rich clusters.) The density of usable sources is unlikely to be high enough to permit the mapping of individual galaxies, except in those cases where there are relatively bright source galaxies along the optic axis. However, statistical studies of galaxies as a function of type, redshift, size, etc., are quite feasible.

6. BLACK HOLES AND NEUTRON STARS

The best prospects for exploring the spacetime around a black hole lie with the $3 \times 10^6\,M_\odot$ hole at our Galactic center. It will be possible to track faint stars as they approach the black hole and predict passages as close as ∼100 gravitational radii. This should permit quantitative tests of the Kerr metric. Advanced pulsar search techniques using giant radio telescopes should lead to the discovery of thousands of binary pulsars in nearby galaxies. Some of these will be observed from within $\sim 10'$ of the orbital plane, and fairly accurate tests of relativity will become possible.

7. STARS

Our Galaxy has over $\sim 10^{11}$ stars, most of which will be typed and monitored. Giant space-borne interferometers should be capable of measuring their proper motions, and their distances will be known quite accurately on the basis of parallax, spectroscopy, and photometry. As the microlensing optical depth is $\sim 10^{-6}$–10^{-7}, stellar events should be initiated roughly every hour and should be predictable. Neutron star lenses, which will be mostly unanticipated, should be found weekly, and black hole events perhaps monthly. Double star lenses are particularly interesting because they form intricate caustics and there is a good chance that microlensing will provide the primary search technique for distant planets. Furthermore, terrestrial planets might be studied and their images deconvolved during a caustic crossing if they trail their star and are magnified a thousandfold for about an hour under the most favorable conditions.

8. WHEN WILL ALL THIS HAPPEN?

The Lyapunov time for contemporary astrophysics is so short that I cannot predict how long it will take to map and monitor the whole sky to faint flux levels. However, because I am supposed to be in the business of prediction, let me guess that someone reading this essay, this year, will witness attempts to accomplish most of what I have briefly discussed plus much more that I lack the imagination to anticipate. Unfortunately, I do not know whether this prediction is one in the field of astronomy or medicine!

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REFERENCES

Blandford, R. D., & Helfand, D. J. 1999, MNRAS, 305, L45

Blandford, R. D., & Hogg, D. W. 1996, Astrophysical Applications of Gravitational Lensing, ed. C. S. Hewitt & J. N. Kochanek (Dordrecht: Kluwer)

Brainerd, T. G., Blandford, R. D., & Smail, I. R. 1996, ApJ, 466, 623

Irwin, M. J., Webster, P. C., Hewett, P. C., Corrigan, R. T., & Jedrzejewski, R. I. 1989, AJ, 98, 1989

Kellermann, K. I., & Richards, E. 2001, ApJ, in press

Kochanek, C. S., et al. 2000, ApJ, 543, 131

Petters, A. O., Levine, H., & Wambsganss, J. 2001, Singularity Theory and Gravitational Lensing (Boston: Birkhaüser)

Porciani, C., & Madau, P. 2000, ApJ, 532, 679

Rusin, D., et al. 2001, ApJ, 557, 594

Schneider, P., Ehlers, J., & Falco, E. E. 1992, Gravitational Lenses (Berlin: Springer)

Soucail, G., Fort, B., Mellier, Y., & Picard, J. P. 1987, A&A, 172, L14

Tyson, J. A. 2000, Phys. Scr., 85, 259

Tyson, J. A., Valdes, F., & Wenk, R. A. 1990, ApJ, 349, L1

van Waerbeke, L., et al. 2000, A&A, 358, 30

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