PROGNOSTICATING THE FUTURE OF GRAVITATIONAL LENSES

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1. Introduction

About 20 years elapsed between my first and second papers on gravitational lenses (Press & Gunn 1973; Press, Rybicki & Hewitt 1992ab). Therefore, the conference organizers have asked me to prognosticate on the future of gravitational lenses. Their reasoning, if I understand it correctly, is that I will likely go to sleep for another 20 years immediately following this conference. So, if I simply look ahead to my very next paper on the subject, I will be in effect prognosticating over two decade's span.

2. Statistics on Lens Publications

In science, like so many other human activities, we march backward into the future. Let us examine, in the grossest of statistical terms, where we have been. Figure 1 shows the number of papers published per year on gravitational lensing. Note the logarithmic ordinate. Einstein's first paper on the subject is the one in 1911 (Einstein 1911). The "bulge" of papers in the mid 1960s is largely due to the prescient work of Refsdal (e.g., Refsdal 1964, 1966), and the fractious, but in some ways farsighted, papers of the Barnothys (e.g., Barnothy 1965, Barnothy & Barnothy 1968).

Looking at Figure 1, it is hard to spot where the first lens, 0957+561, was actually discovered (Walsh et al. 1979). I think that observers were *forced* to discover gravitational lenses by the rising tide of speculative theoretical papers, rather than the other way around!

Now turn, in Figure 2, to prognosticating the future. This is easily done, by the rigorous mathematical technique of linear extrapolation (on a log-linear plot, of course). One sees that by the year 2008, all astronomical work

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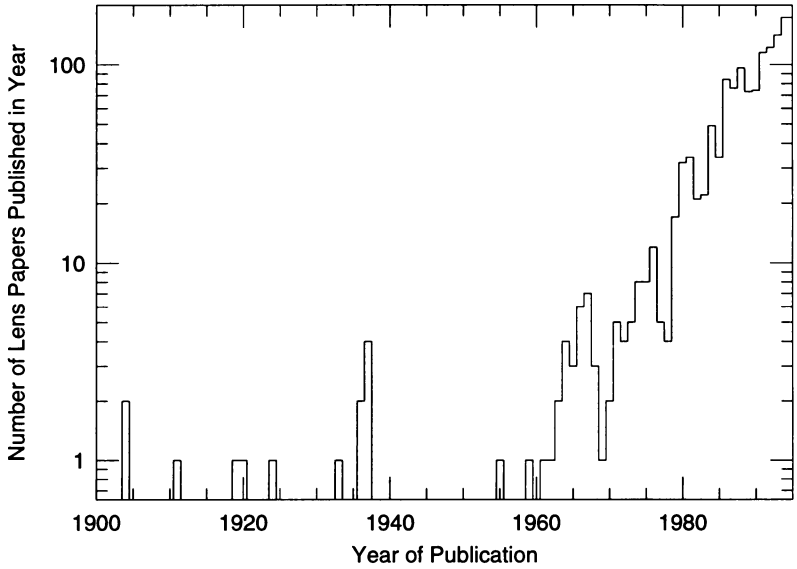

Figure 1. Number of published papers that relate to gravitational lensing, by year. Data from the bibliography of Pospieszalska-Surdej, Surdej & Véron (1994).

will be devoted to gravitational lenses; by the year 2046, gravitational lens work will take over all scientific research; and by the year 2100, all human activity will be devoted to our field.

Actually, the first of these conclusions (the year 2008) has perhaps more than a grain of truth in it. Gravitational lens studies are rapidly becoming mainstream astronomy. Gravitational lens effects, when we include weak lensing, are present along virtually every line of sight out to distances that we now call cosmological – but which will increasingly be the venue of extragalactic astronomy in the post-Keck era. In galactic astronomy, only a tiny fraction of lines of sight are lensed, but our technical capabilities for looking at multitudinous lines of sight are increasing explosively. Gravitational lensing may well disappear as a unique sub-specialty in astronomy, and instead become simply a ubiquitous observational technique. The index of refraction of space will be as much a fact of life to the 21st Century astronomer, as was the index of refraction of glass to his or her 19th Century counterpart.

To fulfill my charge as prognosticator, I must, however, make some more concrete predictions. I divide these into three categories: "New Heavy Industries," that is, large-scale observational efforts that are already gathering force; "Not Whether, But When," that is, advances that seem fully within the reach of foreseeable technology, but that will require dedicated commit-

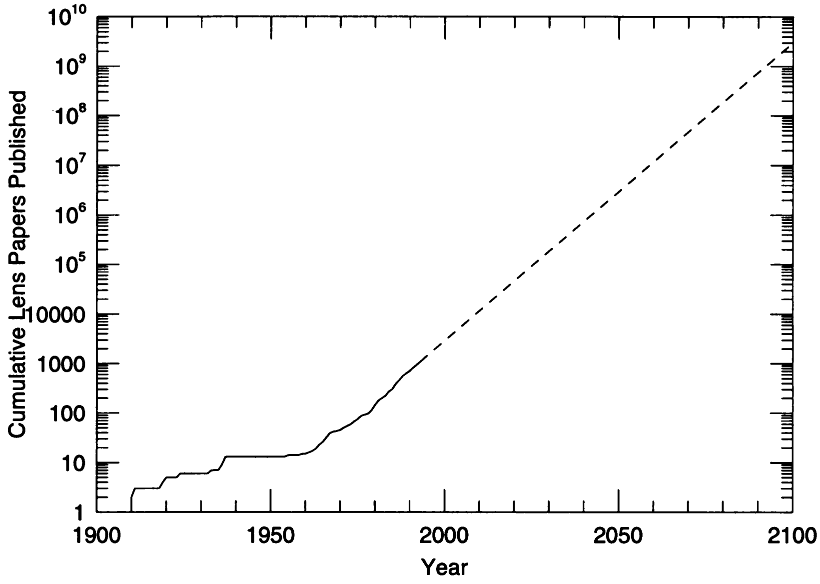

Figure 2. Cumulative number of published papers that relate to gravitational lensing, by year. Data from the bibliography of Pospieszalska-Surdej, Surdej & Véron (1994). The dashed part of the curve is extrapolation to the future.

ment to complete; and "Not When, But Whether," that is, advances that may or may not prove to be possible at all. I have only a few words to say about each item in each category, so my contribution becomes, from this point on, little more than an outline. (Prognosticators, from the Oracle at Delphi to the present, know the wisdom of brevity.)

3. New Heavy Industries

3.1. MAPPING THE SKY IN WEAK LENSING

The number of faint blue galaxies that can be imaged by Keck-class telescopes on the ground (Lawrence in this volume), and HST-class instruments in space, is so numerous that statistical detection of weak gravitational lensing can be done along virtually every line of sight in the sky (see Tyson, and Kneib & Soucail in this volume). It is becoming possible literally to map the distribution of intervening dark (and luminous) matter (Kaiser & Squires (1993), also Miralda-Escudé and Schneider in this volume). Tyson and others have discussed the feasibility of a dedicated dark matter telescope. See also Stebbins, McKay & Frieman (in this volume).

3.2. EXPLOITING GRAVITATIONAL TELESCOPES

Highly distorted, and therefore highly magnified, arclets can be found around virtually every cluster of galaxies at moderate redshift. These images will be increasingly exploited not just to tell us about the lensing cluster, but also (in some cases primarily) to increase the magnification of our terrestrial telescopes for studying the internal structure of faint high-redshift galaxies. See, e.g., Blandford & Hogg, Kneib & Soucail, Smail et al. in this volume.

3.3. LENS INVERSION AS A LARGE-SCALE INVERSE PROBLEM

Instead of using a handful of point-image locations and magnifications to solve for a handful of lens parameters, the lens inversion problem is rapidly becoming one of simultaneous solution, in both the source and lens planes, of millions of equivalent pixels. A recent example is Chen, Kochanek & Hewitt (1995).

3.4. MICROLENS SEARCH FOR PLANETS

NASA Administrator Dan Goldin wants to find extra-solar planets, and he is not a man to be trifled with. We can debate whether this is a scientific or a technological goal; but NASA is in the business of doing both. Personally, I find this a very exciting project in the spirit of Galactic exploration. See Mao & Paczynski (1991), Gould & Loeb (1992) and, more recently, Gould (1994, 1995) and Albrow et al. (in this volume).

4. Not Whether, But When

4.1. MEASURE H_0 TO TWO SIGNIFICANT FIGURES

I am confident that there will be such a measurement, *some day*. Whether it will come from lenses, as opposed to (e.g.) Type II supernovae using the expanding photosphere method, is more problematic. It depends on whether the “perfect” lens comes along: perhaps something like 0218+357, with a delay that can be measured to 2 hour accuracy (see Browne et al. in this volume). One would need the lensed object to be an extended source, to get a handle on the radial mass profile of the lens.

4.2. SHOW THAT $\Lambda < 0.5$ AT 99% CONFIDENCE LEVEL

This will emerge from the continued careful analysis of the statistics of known lenses, not just their number, but also their distributions with redshift, etc. See Rix, Kochanek, and Claeskens et al. (in this volume).

4.3. MEASURE Ω OR Q_0 TO ONE SIGNIFICANT FIGURE

Lens studies will contribute in two ways. First, statistical lens studies will put constraints on the geometry of spacetime at redshifts > 1. Second, dark matter mapping studies will "weigh" the clustered matter. Lens methods are competing with both cosmic microwave background fluctuation measurements on the 1 degree scale, and also with the dynamical data that will be mined from the Sloan Digital Sky Survey and other similar large-scale surveys.

4.4. QUANTIFY THE BINARY POPULATION IN OUR GALAXY

Although it is a messy statistical inverse problem, it is clear that once a significant number of binary microlensing events are in hand, we will know a lot about the population of binary stars in our Galaxy.

4.5. MAP OUR GALAXY'S BAR AND HALO WITH MICROLENSING

The prediscoveries and rediscoveries of the Galactic bar make for an interesting case study in astronomy's "blind spots". See Paczynski (in this volume).

4.6. DETERMINE THE MASS DISTRIBUTION IN GALAXIES AND CLUSTERS GENERALLY

Weak lensing studies will ultimately say a great deal about this. See (e.g.) Schneider, Kneib & Soucail, and Brainerd, Blandford & Smail all in this volume. Kochanek (in this volume) discusses what can come from an approach based on the statistics of strong lenses. Bartelmann & Narayan (in this volume) discuss the exploitation of a subtle effect that allows simultaneous determination of the redshift distribution of faint blue galaxies, and the mass distributions of foreground clusters of galaxies.

5. Not When, But Whether

5.1. MEASURE H_0 TO THREE SIGNIFICANT FIGURES

Am I kidding? It depends on whether there is any possibility of measuring "interferometrically accurate" lens delays, by observing coherence effects between different lens images. (Of course, it also depends on exquisite knowledge of lens mass profiles.)

5.2. MEASURE Ω OR Q_0 TO TWO SIGNIFICANT FIGURES

Now, am I kidding? Probably.

5.3. DISCOVER AN INCONTESTABLE DARK MATTER OR SHADOW SECTOR GALAXY

It will be a breathtaking moment when a future Tony Tyson (or even the present one) shows us a picture with the classic circular pattern of highly distorted arclets, but with *nothing in the middle*. In CDM and related scenarios, baryons and dark matter are not necessarily tied together in all cases, because baryons can be stopped by shocks that allow the dark matter to coast through. Two-stream or other instabilities might then perturb the dark matter, allowing dissipationless gravitational collapse to form completely dark galaxies.

5.4. RULE OUT ALL MACHO MASS RANGES

The implication would be that the dark matter is in distributed form, lending credibility to the belief that it is composed of exotic particles. See Paczynski, Pratt et al., and Alard in this volume.

5.5. MAP STELLAR SURFACES BY LENS CAUSTICS

Jaroszynski & Paczynski (1996) have pointed out that lens caustics are, in a sense, better-than-perfect occulting edges. Where the edge of a physical object (the Moon, say) has a transmission coefficient that varies sharply from 1 to 0, the edge of a lens caustic jumps from an integrable infinity to zero. This causes a new scale – not the Fresnel scale – to enter, with the possibility of sub-picoarcsecond resolution.

5.6. DISCOVER AN $\Omega \sim 1$ POPULATION OF OBJECTS RESPONSIBLE FOR (SOME) QUASAR VARIABILITY

Hawkins (1993, 1995) puts forth the unconventional hypothesis that a part of the variability in quasars not intrinsic to the quasar, but rather due to omnipresent microlensing from a hypothetical population of compact objects with $\Omega \sim 1$.

5.7. DETECT A MICROLENS BY DIRECT COHERENCY OF IMAGES

We first learned to find gravitational lenses in cases where they have multiple images. Later, we learned to find them in microlens surveys when they cause time-varying magnifications. We are now learning to find them statistically in the small shears of faint blue galaxies.

There are at least two other ways that lenses might, in certain circumstances, be found: (1) time autocorrelation on unresolved, time-varying, objects; and (2) direct detection of time-lagged coherency on non-varying sources. As I discussed in my talk, and won't repeat here, the latter idea contains conceptual pitfalls that are clearly avoided only in the case of *extremely* small source sizes.

Still, I have a nagging feeling that there is a pony (or kangaroo) somewhere in the pile of papers that have been written on one or another aspect of coherency effects in lensing. See Schneider & Schmid-Burgk (1985), Mandzhos (1981), Deguchi & Watson (1986), Peterson & Falk (1991), Krauss & Small (1991), and Spillar (1993), as well as the previously mentioned Jaroszynski & Paczynski (1995). For the microscopic case ("femtolensing"), see Gould (1992), and Ulmer & Goodman (1994).

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