Gravitational Lensing: Recent Progress and Future Goals
– Conference Summary

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Abstract. There are three neighborhoods of interest in gravitational lensing: that of the source, that of the lens and that of the observer. Since the last major meeting on lensing, the 1995 IAU Symposium, No. 173, in Melbourne, considerable observational and theoretical progress has been made in our understanding of the first two of these, while considerable technical progress has been made in the third.

1. Confession

Predicting whether a conference will prove exciting or ho-hum has always been difficult for me. So it is with especially deep admiration that I congratulate the Scientific Organizing Committee on the superb job they have done (at least until this point) in selecting speakers for this meeting. We have been treated to an excellent smorgasbord of reviews, background talks and exciting new results. But on second thought, perhaps the SOC did not have so demanding a job after all. The poster presentations have been so outstanding, with such very high signal to noise, that a more or less random selection from among the submitted abstracts might have produced an equally good set of talks.

2. Question

This said, let me pose a question which may seem churlish: why did we have this meeting? After all, the cost of such a gathering is very considerable, especially in person hours spent preparing for it and in actual attendance, but also in the cost of travel and discomfort – including circling over Logan airport for several hours, being diverted to Hartford, New York or Washington, and being drenched in downpours.

We’ve heard ourselves referred to by several of our speakers as “the lensing community.” If there really is such an entity, it is one that spontaneously fragments into constituencies. There is a microlensing community and there are strong and weak lensing communities, with the latter again split into those who study weak lensing by identifiable objects and those who study the properties of the potential field without little regard for the objects responsible for it.

Were you to look at a list of astronomical meetings in any given year, you would find that they fall into two broad categories. The majority of meetings are organized around some class of astronomical phenomenon: peculiar A stars, high redshift galaxies, molecular clouds. But many meetings are organized around
specific techniques rather than phenomena: long baseline interferometry, adaptive optics, TeV astronomy. Typically these are in areas where the technology is new or rapidly changing. And so there is a second question related to my first question. Is this meeting a phenomenological meeting or is it a technological meeting?

The list of the phenomena covered by participants at this meeting is very long. One is impressed at how large a fraction of the astronomical universe has been discussed: planets, stellar surfaces, quasars and their hosts, the microwave background. Nobody would ever organize a meeting with so wide a range of topics; should we conclude, by elimination, that this is a technique meeting?

In addressing this question it is helpful to look at the classic gravitational lensing diagram, the variants of which Virginia Trimble traced back over two hundred years. The figure has three sections – the source end, the observer end, and middle, where the lensing takes place. Phenomenon oriented meetings are usually concerned with the source end of the diagram. Technique oriented meetings are usually concerned with the observer end of the diagram. What makes this meeting unusual, distinguishing it from most other meetings, is that the principal interest of most contributors at this meeting has been neither at the observer end of the diagram nor at the source end but the machinery in the middle. We would seem to be in a class by ourselves (though not quite if we count students of the interstellar medium).
The subject of our meeting goes by three different names, each of which carries somewhat different connotations. In French it is called “mirage gravitationnel,” which tends to emphasize the experience of the observer. Some of our speakers describe their use of “gravitational telescopes.” For them the effect is simply a tool which gives them more photons or higher resolution from an otherwise faint or small source. The term “gravitational lens” emphasizes the intermediate optics rather than the astronomical sources or the observer.

If I were to characterize where our contributors’ interests lie, I would guess that 25% are primarily interested in the sources and 15% are primarily interested in the detectors and analysis techniques with the remaining 60% interested in the lenses themselves, though of course there’s scarcely a person in this room who isn’t interested in all three.

The reason for interest in the lenses is manifest – observations of the deflections, distortions and delays introduced by lensing permit one to measure the masses of intervening objects. The circumstances under which astronomers can measure masses are so rare that they jump at the opportunity.

The history of the measurement of masses of clusters of galaxies drives this point home. Zwicky and Smith were the first to measure the mass of a cluster, but the answer they found was so far from the expectations of the day that the astronomical community chose to ignore it. By the mid-1970s measurements of X-ray gas profiles and temperatures more or less confirmed the optical velocity dispersion measurements, but the astronomical community was still in a state of denial about the consequences. Doubts and suspicions have lingered into the present, so people have seized upon gravitational lensing as a means of resolving the issue.

Our classic lensing diagram, as drawn here, is grossly exaggerated, and represents a rather bad case of wishful thinking (something to which we, as astronomers, are in no way immune). Our figure pretends to be a case of strong imaging. The widest separations, of order 1 arcminute – a third of a milliradian – are produced by clusters of galaxies. Strong lensing by galaxies produces deflections of several microradians. Microlensing within the Local Group produces deflections of nanoradians, and microlensing on cosmological scales gives deflections measured in picoradians. Even for the largest deflections we consider, this diagram collapses to a line if one tries to draw it to scale. The exceedingly small solid angle of influence of the lenses we seek to study drives us to extremes in terms of photometric accuracy, astrometric precision and in numbers of objects needed to produce the wanted effects. In some cases that quest borders on the quixotic. The fact that so many of us are willing to undertake such efforts is testimony to how important we believe the results might be.

I will use our classic diagram in reviewing what we’ve heard and seen in the last five days, grouping together results at the observer end, results at the source end and results in the middle.

3. The Observer

The lensing community can take considerable pride in the extent to which some of our members have led the larger astronomical community in experimental techniques. Chief among these has been the development large format CCD
detectors. When Tony Tyson first undertook measurements of galaxy-galaxy lensing in the early 1980s, he used photographic plates. We have all had a good laugh at the old-fashioned darkroom timer that was called out of retirement to keep our speakers in line. But remember that well into the 1990s, the photographic plate, despite its 1% quantum efficiency and its horribly non-linear response, has remained a valuable tool in our field because of the small size of solid state detectors. The MACHO and EROS groups, Tyson and Bernstein, and more recently Gerry Luppino and his group have been world leaders in constructing large area solid state imagers.

A number of gravitational lens programs has been very large in scale, requiring a degree of organization and coordination rarely seen in astronomy. The MACHO and EROS collaborations, in particular, have brought the culture of particle physics to ground based astronomy. The CLASS collaboration (Myers), the MIT surveys (Winn) and the ACT effort (Prouton) have brought a new style to radio observations as well, with radio telescopes spending almost as much time slewing between objects as observing.

I wish I could say that optical astronomers have done as good a job as radio astronomers in searching for new lenses. Strong lensers (myself among them) have not been as effective in marshalling the resources necessary. There is a crying need for wide field optical telescopes of moderate size with silicon focal planes to carry out survey work. On a more positive note, the PLANET and G-MAN collaborations have been spectacularly successful in assembling the instruments necessary to carry out round the clock monitoring of exotic lensing events.

Lensers have also lead the way in software. FOCAS was an early effort on the part of Tyson and his collaborators (Jarvis et al. 1981) to deal with unprecedentedly large numbers of images. The nearly total automation of the MACHO project may not seem particularly noteworthy to radio or X-ray astronomers, but it is quite remarkable among ground-based optical efforts. The OGLE program, we are told, is automated to the point where a program field is specified and the reduced data are emailed to a designated recipient. Image differencing is another development which, while straightforward in principle, has only now been made to work, and which promises major improvements in sensitivity. It is remarkable that Crotts and his collaborators and now Alard and Lupton (1998) have been able to press to the photon limit.

Alas one must worry not only about photon statistics but also systematic errors. The efforts of the various weak lensing groups to remove myriad sources of systematic image distortion have been nothing short of heroic. Chris FASSNACHT and Leon KOOPMANS have likewise pushed the envelope in their exceedingly accurate radiometric measurements. We have also seen extraordinarily high dynamic range measurements in the ring of B0218+357 (BIGGS) which will help in its modelling. The UH optical astronomers are the first I know of who have dared to show the Hubble Deep Field image side by side with their own. Theirs may be somewhat less deep, but it is certainly very much wider, and that is clearly what we need for weak lensing.

Some measure of the excitement generated by the phenomenon of gravitational lensing can be had by noting the prominent role it plays in the justification for many of the major projects now being evaluated by the US National Research
Council’s decennial survey of astronomy. We have heard lensing invoked as a justification for NGST, for an 8m ground based “dark matter telescope”, for the VLA+ upgrade and for the Square Kilometer Array. Lensing likewise figures prominently in the programs for the Advanced Camera for Surveys on HST, Chandra, XMM, SIM and Planck.

4. Sources

Lensing has provided data about sources which could not otherwise have been obtained. Hans-Walter Rix has shown us that the hosts of high redshift quasars are surprisingly easy to see if one uses lensing to boost the resolution of NICMOS. It is not atypical to find that the increased resolution produced by a lens is more important than the increased photon count.

A number of speakers and presenters have shown us how microlensing can be used to set limits on the sizes of quasar components (Agol; Yonehara) both in the optical and in the radio. Some of our theorists have outlined how one might use a caustic moving across a quasar to study the structure of quasar accretion disks.

We have heard from Penny Sackett and others about how microlensing can be used to study the surfaces of stars, and in particular to check models of limb darkening and for the presence of starspots. Such stars have diameters (if I heard correctly) of 100 nanoseconds.

Bob Nemiroff told us how gravitational lenses give us information about otherwise elusive gamma ray bursts. It should be noted that one of the two subclasses of gamma ray bursts, the short ones, have not yet had host galaxies measured. Lensing may therefore provide the only limit on the redshifts of these objects, albeit a weak one.

And we have heard, en passant, about how gravitational lensing has twice given us the record holding high redshift galaxies, first in a CNOC cluster (Yee et al. 1996) and then in 1358+62 (Franx et al. 1997).

It is notable that we have not had at talk about the use of gravitational telescopes to improve the spatial resolution of the submillimeter bolometer array (SCUBA) on the JCMT in the study of dusty galaxies at high redshift. Some of the best work in that field has been done using lensing (e.g. Smail et al. 1997), and the people who did it have in years past been active participants at gravitational lens meetings. I doubt that our SOC slighted this work; rather, I suspect that these individuals treat gravitational telescopes as just another weapon in the astronomical armory, and that they feel their time is more wisely spent going to meetings where the high redshift universe is the principal focus.

5. The Lenses

The majority of the papers at this meeting have emphasized neither the sources nor the observing and detection but the deflection, distortion and delay of light by intervening masses. Until now the masses of astronomical objects have been measured by observing the bound orbits of gas, stars or galaxies in gravitational potentials. Now we study mass distributions by studying the unbound the orbits
of photons. Until now we have relied there being stars, gas or galaxies present to study potentials. But now we know, at least on average, that we can count on a certain number of background sources to be lensed by the foreground objects we wish to study.

Lensing might not be quite so interesting were the universe not pervaded by dark matter. We suspect that 90% or more of the matter in the universe is non-baryonic, and that a major fraction of the baryonic matter may itself be dark (though not quite so totally and unrelentingly dark as the non-baryonic stuff). It is with a combination of embarrassment and frustration that we explain to people outside astronomy that we cannot observe 90% of the universe. Gravitational lensing offers us a chance to redeem ourselves.

What our friends outside astronomy don’t know is that luminous matter is at best a treacherous tracer of dark matter. We know that light fails to trace mass in the Milky Way and other galaxies, and we suspect that galaxies may fail to trace light in bound clusters of galaxies and in yet larger structures in the universe. So we are driven to gravitational lensing as the most reliable means of studying the distribution of dark matter.

There has been spirited discussion of the observation of gravitational microlensing toward the Magellanic clouds and its implication for the composition of the dark halo of the Milky Way. While the MACHO collaboration has argued that most of these events arise from compact objects in the galactic halo (Alcock et al. 1997), we have heard forceful arguments for self lensing by the LMC (Evans). Given theorists’ creativity in coming up with models, the issue is likely to be settled only with a very much larger set of events than we presently have. However the question is resolved, we will have learned an enormous amount from the microlensing searches.

Another subject which generated fascinating discussion was the gravitational potentials of galaxies for which time delays have been measured. There has been superb progress on the observational front. At the Melbourne IAU symposium (Kochanek and Hewitt 1996) even the time delay for B0957+561 was a matter of contention. Today there are 8 systems with measured time delays, with two of those delays reported for the first time at this meeting. This is the result of prodigious, painstaking effort on the part of radio and optical observers. It is easy to forget that a set of 50 data points demands 50 times the effort (perhaps even more, given the spacing requirements) than a single data point. The first reported delays for RX J0911+0551 and CLASS B1600+434, from data obtained by Ingunn Burud and collaborators with the NOT, were breathtaking. Tommy Wicklind’s confirmation of the time delay for PKS B1830-211 using single dish molecular absorption spectra was another tour de force.

There are several schools regarding the interpretation of time delays. There are those who choose parameterized models for potentials (Bernstein; Chae) and those who despair of adequate parameterization and instead adopt a non-parametric approach (Saha; Williams). There are those who insist that every detail of the gravitational potential (most importantly its logarithmic slope) must be measured from the lens itself. On the other hand are those who are willing to bring their knowledge of the dynamics of other galaxies to bear on the problem. The former are the perfectionists, members of the “golden lens” school. The latter are the compromisers, members of the “warts and all” school. As a
member of the latter, I will exercise my prerogative as summarizer and note that if one adopts a simple model and observes a small scatter in the derived values of the Hubble constant, one might not be making so large an error in transferring one’s hard won knowledge of galaxy dynamics to galaxies for which the dynamics are nearly impossible to measure. In this regard my reaction to Liliya Williams' non-parametric models was exactly the opposite of Roger Blandford’s. Where he drew the conclusion that the Hubble constant was hopelessly uncertain, I was pleased to see how little the Hubble constant depended on anything except the logarithmic slope of the potential, a result also emphasized by Olaf Wucknitz.

In his review, Ed Turner opined that lenses now give the best value of the Hubble constant. Considering the care that has gone into the HST Cepheid Key Project, especially in estimating their error budget, I don’t think we are yet in a position to claim this particular piece of high ground. But if we see redshifts for RX J0911+0551 and HE B1104–1805, and if in another year the present time delay results don’t change dramatically, it might be that even unbiased observers (creatures rarer than unicorns) would agree with him.

Both those of the “golden lens” school and those of the “warts and all” school agree that many new lenses are needed. Survey work is sine qua non of astronomy. CLASS (Browne; Myers; Rusin) has been gloriously successful in producing new cases, including two of those for which we now have delays. Optical searches have until now lagged behind, especially when one folds in the fact that 90% of quasars are radio quiet. The Sloan telescope in the north (Pindor) and the VST in the south may go part way toward redressing this imbalance, but for reasons which are in no way fundamental (e.g. pixel size, programatic constraints) neither is ideally suited to the task of finding strong lenses.

The strong lenses have also given us a picture of the luminosity evolution of early type systems which is completely independent of the work done in clusters of galaxies. It is amazing that the results reported by Kochanek, determining parameters for the so-called “fundamental” plane using lensing galaxies, agree as well as they do with results obtained for clusters using conventional methods. Who would have thought that galaxies selected by mass would agree as well as they do with galaxies selected by light?

Brian McLeod spoke about the non-gravitational aspects of propagation of multiply imaged quasar light through lens galaxies, giving us a unique handle on the properties of the ISM at high redshift. In the course of that he was able to show that, for whatever mysterious reason, lensing has helped us to find two of the intrinsically reddest quasars known in the universe.

It must be remembered that strong gravitational lenses are poorly designed and, moreover, fabricated from inferior materials. The lens material typically exhibits huge variations in its index of refraction due to the substantial percentage of its mass in stars and MACHOs. The stars must introduce microlensing even if MACHOs do not. Here again we’ve begun to address questions which I would not have thought possible. While there is a near degeneracy between the rms mass of the microlenses and the fraction of the intervening mass in condensed objects, there is hope for separating these two effects in the higher order statistics of light curves. One need only remember that Sjur Refsdals’s two curves, one based on a peak and the other based on a plateau, did not have the
same shape in his log-log “exclusion” diagram. Koopmans’ results on CLASS B1600+434 are all the more fascinating for being a case of observation not yet confirmed by theory. While microlensing is noise to those who wish to measure time delays, perhaps we must count ourselves lucky that at least some of our lenses suffer from it.

The developments in galaxy-galaxy lensing have been very encouraging. Several groups have described their efforts (Brainerd; Casertano; Fischer; Smith) and, quite remarkably, they all agree with each other. We still haven’t seen the cutoff expected in our isothermal sphere models and Hank Hoekstra’s result for groups lead me to suspect that we may never see one. But there are other things to be tried, including testing of the isothermality hypothesis. Phil Fischer showed that variations in the Sloan survey PSF were not so malignant as to swamp the galaxy-galaxy lensing signal.

Probably only at meetings on adaptive optics do point spread functions receive more attention than they did at this one. Hans-Walter Rix described the NICMOS PSF as one that only a mother could love. I suspect these words will find new application as people analyze the data obtained with new generations of wide field cameras now coming on line.

Weak lensing observations of clusters have moved from the regime of marginal detection to that of serious astrophysical tool. Nick Kaiser has shown us that there is surprisingly little radial bias in the luminosity profiles of clusters of galaxies – this from the man whose name is most closely associated with the concept. It’s far too soon to accede on this point – there are troubling differences between lensing results and those obtained from optical and X-ray data. I wonder whether we shouldn’t introduce a few weak lensing “standards”, in the same way we have adopted photometric standards, to ensure that everyone is on the same system. A point that was made many times, which may nonetheless have failed to penetrate the stubbornest of listeners, is that “seeing is everything.”

With the successful launch of Chandra and the promise of XMM and several CMB imagers, we have the prospect of comparing 4 different estimators of mass and substructure in clusters of galaxies. A crucial issue in this regard is the boundary between galaxy and cluster – where the galaxy ends and the cluster begins. Priya Natarajan’s results have whetted our appetite for further investigations of this sort.

On the scales so large that structure is still linear or weakly non-linear, scales on which one must study fields rather than objects, we have heard about mean polarizations (Wilson) and polarization correlations (Wittmann) and aperture masses (Schneider) as alternative vehicles for studying the the power spectrum of mass fluctuations. The complementarity (a word that brings down the duck with $100) of weak lensing results and CMB measurements has been repeatedly emphasized as has the point that these probe large scale structure at different epochs (Jain; Seljak). It is a measure of how exciting these prospects are that people are willing to undertake huge programs of extraordinarily delicate measurement. The signal may already have been seen but the uncertainties, almost all of them systematic, are as yet too poorly understood for firm conclusions to be drawn.

Next there is the small matter of the universe itself. In addition to the dimensioned parameter $H_0$, lensing can in principle tell us about dimensionless
parameters, the cosmological density parameter $\Omega_m$, and the dimensionless version of the cosmological constant (or the vacuum energy density), $\Omega_\Lambda$. There are several approaches to measuring these. The largest effect involves the numbers of lensed systems (Helbig), but as yet the luminosity functions for unlensed objects and the mass functions (and shapes) of lenses are too poorly known for these to provide strong limits. There are other effects, such as comparison of the sizes of Einstein rings for objects at different redshifts behind a lens (Link). We may get lucky in this regard and find a lens with simple geometry and multiple sources each multiply imaged.

Finally let’s return to our own neighborhood and consider a different kind of dark matter – planets. We have seen that planet detection is a serious possibility (Dalil; Gaudi) and will be even more likely with the advent of SIM (Boden). We enjoyed an outlaw poster claiming a planet of $5 \, M_J$ has already been observed in a microlensing event (Bennett et al. 1999).

6. Broad Issues

Several themes emerged in the course of the meeting which don’t fit easily into our observer, source or lens pigeonholes. The first of these regards a sea change in the way we do astronomy. Many of you saw the article in Sunday’s NY Times Magazine called “The Loneliness of the Long Distance Cosmologist” (Panek, 1999). It describes how the nature of the astronomical enterprise in general, and how measurement of $H_0$ in particular, has changed from the solo effort of a lone wolf carried out at the prime focus of a unique telescope to the concerted effort of a large team, often using multiple telescopes (which many members of the team may never even have seen). While there may still be room for lone wolves in gravitational lensing, team efforts, with the attendant headaches, the massaging of egos and the compromising on means and ends, seems to be the order of the day. Like it or not, we are destined to live in an era of cloying and lame acronyms.

A second recurring theme, not unrelated to the first, has been that of the “exclusion” diagram. We have seen many instances of observations that, while they rule out the large volumes of model space, produce allowed volumes (error ellipsoids, to first order) whose principal axes happen not to lie parallel to the axes of the model space of interest. The lone wolves among us show a strong preference for measurements which produce nicely aligned error ellipsoids. The team players don’t care whether ellipsoids (singly or from more than one measurement) and axes are aligned or not, as long as the resulting volume is small. I can sympathize with the lone wolves on aesthetic grounds but the future belongs to the tilted ellipsoids.

7. Bread and Butter Issues

The success of the Scientific Organizing Committee has been surpassed only by that of the Local Organizing Committee. With the exception of a friendly visit by the local firefighters our meeting has proceeded seamlessly. The accommodations have been excellent, the meeting room and poster area ideal, the pastry and coffee far above average, and the dinner cruise up and down the Charles
and around a moonlit Boston harbor most memorable. We owe the chair of the LOC, Tereasa Brainerd, our host institution, Boston University, and our sponsors, the US National Science Foundation, NASA, and Boston University, considerable thanks for making this meeting as productive as it has been.

Perhaps the most appropriate place to end is with a call for volunteers to organize a gravitational lens meeting in 2002!

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