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History of Bell Labs Physical Research, 1980–2006

The Development of Gravitational Lens Mass Tomography

J. Anthony Tyson

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Applying CCDs to Astronomy: Discovery of the Faint Blue Galaxies

Triggered by a discussion with George Smith (co-inventor of the CCD with Bell Labs colleague Willard Boyle), I began experiments with charge coupled devices. Ultimately, this resulted in a series of CCD cameras of increasing size on various telescopes. Amazingly, we found thousands of faint galaxies that were invisible on deep photographic plates. Seeing though a high-density forest of galaxies, possibly distant galaxies, there was a high probability that some distant galaxies would be warped via gravitational lensing by foreground massive galaxies. With John Jarvis, we developed a software package, FOCAS, for automated surface photometry and morphological classification of faint images [1-4]. Our goal was to measure the shapes of galaxies to search for statistical gravitational lensing of background galaxies by foreground galaxies. We discovered that the number density of galaxies increased like a power law with faintness, with implications for how far away they are and for the process of galaxy evolution [2,4]. By 1980, we had tested our photometry and lensing software with simulations, seen hints of a galaxy-galaxy lensing signal, and hired postdoc Frank Valdes.

Statistical Weak Lensing

Large mass concentrations, measuring gigaparsecs in size, would systematically warp background images over surrounding areas of the sky. A rotation or large-scale vorticity would also cause separate special alignments of distant galaxies. Before large CCDs became available, I worked with scientists at Eastman Kodak to increase the sensitivity of their large photographic plates. Jarvis and I undertook a search for these two effects, cosmological distortion and rotation, in 1981. We used all the deep photographic imaging data and measured the orientations of some 50,000 faint galaxies. With Valdes and Jarvis, we found a null result [5] suggesting that the amount of dark matter in the universe was less than the critical value. In this early paper we worked out the tensor formalism for weak lensing and what later would become known as "cosmic shear."

The development of FOCAS also enabled our pursuit of statistical weak lensing of galaxies by foreground galaxies. Our first attempt was to use the photometric catalogs of shapes, orientations and brightness of all the galaxies detected on our deep photographic plates. Splitting the 50,000 galaxies into "foreground" and "background" based purely on brightness produced a 2-sigma galaxy-galaxy lensing signal. Rather than claim a detection, we chose to use this marginal result to put an upper limit on average galaxy mass and dark halo size [6]. The firm detection of galaxy-galaxy lensing was obtained with the repaired Hubble Space Telescope in 1994 [7]. The wholesale application of weak lensing as a tool for the direct exploration of mass in the universe over large volumes had to wait for the development of new imaging technology.

Development of CCD Imagers and Low Light Level Techniques

To reach ultra low light levels, we had to average many separate exposures. Unfortunately, the many artifacts on photographic plates averaged down too slowly. My frustration with photographic plates in the late 1970s, and the pressing need to look sensitively at lensed quasar candidates at optical wavelengths for evidence of the lensing galaxy, sparked my interest in the emerging CCD technology. In 1978 Bob Lee and I built one of the first CCD cameras, based on an early buried-channel CCD of only 100x100 pixels. Using this camera with colleagues at Lowell Observatory we imaged the host galaxy of the nearest quasar [8].

One problem had been solved by the switch from photographic plates to CCDs: rather than separate plates, each with its own artifacts, it was now the same identical imager for each exposure. This turned out to be crucial. It was possible to generate a high-fidelity image of the fixed artifacts on the CCD and then use this to eliminate them from the data. Experimenting with ways to eliminate the fixed garbage patterns on these early CCDs, I developed the shift-and-stare technique of image reconstruction. This combination of special imaging steps and data processing enables the reconstruction of an image completely free of the low-level cosmetics of the CCD, opening new possibilities in low light level imaging [9, 10]. Labs management liked to see applications of one invention (CCD) to other difficult experiments which would likely need to invent new technology in its own right. Upgrading to a 320x512 pixel back-illuminated CCD with 60% quantum efficiency in 1983, I decided to look deeply at the sky for the first time.

The idea was to deeply image a small field going through the forest of galaxies. Using engineering time on the 4-meter telescope at Cerro Tololo Inter-American Observatory, Pat Seitzer (U. Michigan) and I took many 10-minute exposures of a field near the south galactic pole in several color bands. I had obtained a very deep photographic plate of this same field the previous year. While the plate showed clearly only two stars in this area, the co-added CCD color image revealed several hundred faint blue galaxies. Extrapolating to the whole sky, there would be over thirty billion. We then undertook a survey over the next few years of twelve random fields, using the 4-meter telescope. This survey showed for the first time the power-law galaxy counts as a function of wavelength, with implications for both galaxy evolution and cosmology [11-13]. With my student Raja Guhathakurta, we added a fourth filter for the UV and obtained the first constraints on the redshift distribution of the faint blue galaxies [14] by looking for galaxies dark at UV and blue wavelengths, a 'color-redshift' technique which Chuck Steidel (Caltech) and his students later perfected for finding very high redshift galaxies.

A large area CCD imager for weak lens studies could in principle be made from a mosaic of large CCDs. The problem was that the yield on science grade 2048x2048 CCDs was nearly zero. In 1987 I started on a project to build a 4-CCD mosaic. Working with engineers at Tektronix to solve their yield problem, partly through application of a remote thermal imaging technique Paul Kolodner and I had developed at Bell Labs [15], we finally got our first 2048x2048 chips in 1995. With postdoc Gary Bernstein, we built the first large-area CCD mosaic camera system [16] and installed it on the CTIO 4-meter telescope. Dave Wittman, Gary Bernstein, and I supported this camera system as a facility instrument on the 4-meter for the whole community. In a few years' time, this camera system (called the Big Throughput Camera, BTC) made several breakthroughs in astronomy, including the discovery of the acceleration of the expansion of the universe (dubbed "dark energy"), using supernovae. The BTC was used in our weak lensing work [17] and ultimately led to a national effort, the Large Synoptic Survey Telescope.

2-D Statistical Weak Lensing: Mass Mapping to Cosmic Shear

Even before the BTC was ready, I decided in 1988 to search for weak lensing around clusters of galaxies using a 1024x1024 pixel CCD on the 4-meter telescope. Using shift-and-stare imaging through multiple bandpass filters, the first clusters I imaged showed a highly significant systematic alignment of the faint blue galaxies around the cluster! [18, 19]

I soon realized that measuring the net alignment successively around a grid of points on the sky could in principle generate a map of the projected gravitational potential. Examining the relationship between mass distribution and the induced shear of the background galaxies in simulations, I developed a kernel integral technique for inverting the shear to produce a projected map of the gravitational potential of the lens mass [19, 20]. Nick Kaiser (U. Hawaii) and students developed an equivalent inversion using FFTs [21]. Together with postdocs Phil Fisher and Ian Dell'Antonio, we mapped the mass in many clusters of galaxies, showing that their mass is dominated by a dark matter halo, and that the dark mass has occasional substructure [22].

With the BTC, the search for general alignments of faint galaxies due to intervening dilute dark matter, "cosmic shear," could be undertaken. In 1991, my Princeton student Jordi Miralda-Escude undertook a theoretical analysis of this effect in different cosmologies for his PhD thesis. To actually detect this cosmic shear, we had to control the optical aberrations to better than 100 ppm. We used the faint stars in the foreground as the control, convolving the image with a filter that makes them round [20, 22]. Images also had to be de-warped to take out field distortion. With Dave Wittman we designed software pipelines for the entire process. By 1997, all the elements were in place, and we took "blank field" deep multi-band imaging with the BTC, and in 2000 we published the first detection of cosmic shear [23]. The correlations in shear of the faint galaxies were measured out to large angles, constraining cosmology. Weak lensing is a purely physics-based measurement of mass in the universe (only shapes, angles, and redshifts are measured) and does not rely on heuristic metrics such as "standard candles" or on proxies for mass such as luminosity. Some of our group at Bell Labs in 1998 are shown below.

Left to right: Tony Tyson, David Kirkman, Ian Dell'Antonio, David Wittman, and Gary Bernstein.

3-D Mass Tomography: Probing Dark Matter and Dark Energy

Lensing surveys of dark matter came up with only about 30% of that required for closure. Combined with the recent cosmic background radiation anisotropy results implying a flat overall geometry for the universe, this suggests some additional non-clumping form of mass-energy to make up the difference. At the same time, results from studies of distant type-1 supernovae suggested (if the supernovae are indeed standard candles) that the universe is accelerating its expansion. If so, then this may be evidence for dark energy of about 70% of closure density. What is the physical nature of dark matter and dark energy? If we could measure the number and mass of dark matter over-densities (aka. clusters) as a function of cosmic time, then we could discriminate between different models of dark energy. This is because different equations of state and amounts of dark energy produce different rates of growth of dark mass structure.

To probe this development of mass clumping with cosmic time we needed to both map the sky with weak lensing and also place the detected clusters at their correct redshifts. This is possible from multi-band imaging alone, via a combination of weak lens shear and color-redshifts of millions of source galaxies: 3-D mass tomography [25]. The idea is that more distant source galaxies are more strongly sheared, and one can solve for the redshift of the cluster from the shear data alone. Working with David Wittman and several other collaborators, and using deep 4-band BTC data in one 0.7 degree BTC field, we found a cluster via weak lens shear, placed it at its correct redshift using shear vs. color-redshift of the sources, and confirmed this redshift via spectroscopy using the Keck telescope [26]. This was the first demonstration of full 3-D mass tomography. To probe the physics, we needed to apply this to a significantly larger area of the sky in order to have a sample of mass clusters over a large volume and over a large look-back time.

To address this, we formed a collaboration to undertake deep four band color imaging of 30 square degrees of the sky. This project was called the Deep Lens Survey (DLS), and it was granted 150 dark nights on the NOAO 4-meter telescopes over 5 years. The DLS began in 1998 and included a collaboration of astronomers nationwide. A critical step in the process is the calibration of the color-redshift for our filter system via sample spectra of selected galaxies using the low-resolution spectrograph on the Keck telescope. We obtained calibration spectroscopy for over 1000 DLS faint galaxies. We then compared the observed number vs. mass vs. redshift distribution with n-body simulations of cold dark matter plus various dark energy equations of state. This gave the first hint of the nature of dark energy. At the time we were the only group doing 3-D mass tomography—DLS remained the deepest lensing survey for 20 years. In 1996, we decided to propose a far more ambitious project, pushing technology beyond the state-of-art in three directions: large optics fabrication, gigapixel CCD focal plane, and real-time processing and analysis of petabytes of data.

The Large Synoptic Survey Telescope

As a cosmological tool, the BTC produced only 30% precision, but to reach the required percent-level precision for the dark energy equation of state, we would need to survey about 20,000 square degrees, accurately measuring the shear of billions of distant galaxies. There was no telescope/camera facility capable of this anywhere in the world. Rob Pike and I socialized the idea of a "Super SDSS'—an ultra-deep version of the shallow Sloan Digital Sky Survey, then just getting under way. In 1998, I rounded up some other leaders in astrophysics among fellow NAS members and submitted a proposal for the Dark Matter Telescope to the upcoming NRC decadal survey of astronomy and astrophysics. The 2000 decadal survey ranked it highly. Recognizing its potential to do more than map dark matter, they changed its name to the Large Synoptic Survey Telescope.

Thus, we began a project to build a unique wide-field high-throughput facility called the LSST [27, 28]. The LSST is a three-mirror ground-based telescope with an 8.4m diameter primary mirror, coupled to a 3,200-megapixel CCD imager [29]. It would reach galaxies billions of light-years distant in only 15 seconds, enabling a survey of the entire visible sky, producing a unique digital color motion picture of the universe. Every night for a decade, LSST takes images of the sky using six different optical filters. Each image covers an area as big as 40 full moons, and the telescope can move between different positions in less than five seconds. In this way, the telescope will image the entire visible sky every 3-to-4 nights. LSST can detect objects that have changed in brightness, like supernovae, or in position, like asteroids. LSST's light-collecting power and sensitive camera will discover ~17 billion stars and ~20 billion galaxies never seen before. While at Bell Labs in 2003, I became the founding director of this ambitious project, which was later ranked as the top priority for new US astronomy facilities. Thanks to support from Bell Labs, this project grew from a dozen collaborators to over 1,000 in a decade via a grassroots process. A public-private partnership, most of the construction costs were ultimately supported by the National Science Foundation and the Department of Energy.

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