GRAVITATIONAL LENSES AND THE STRUCTURE AND EVOLUTION OF GALAXIES

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The grant has supported the completion of 10 papers and 3 conference proceedings to date.

During the first year of the project we completed five papers, each of which represents a new direction in the theory and interpretation of gravitational lenses. In the first paper, "The Importance of Einstein Rings," we developed the first theory for the formation and structure of the Einstein rings formed by lensing extended sources like the host galaxies of quasar and radio sources. We applied the theory to three lenses with lensed host galaxies. For the time delay lens PG 1115+080 we found that the structure of the Einstein ring ruled out models of the gravitational potential which permitted a large Hubble constant (70 km/s Mpc). In the second paper, "Cusped Mass Models Of Gravitational Lenses," we introduced a new class of lens models where the central density is characterized by a cusp ($\rho \propto r^{-\gamma}$, $1 < \gamma < 2$) as in most modern models and theories of galaxies rather than a finite core radius. In the third paper, "Global Probes of the Impact of Baryons on Dark Matter Halos", we made the first globally consistent models for the separation distribution of gravitational lenses including both galaxy and cluster lenses. We show that the key physics for the origin of the sharp separation cutoff in the separation distribution near 3 arcsec is the effect of the cooling baryons in galaxies on the density structure of the system. The cosmological density in cold baryons must be approximately $\Omega_{b,cool} \simeq 0.02$ in order to explain the lenses. The last two papers explore the properties of two lenses in detail. The first of the two, "Constraints on Galaxy Density Profiles from Strong Gravitational Lensing: The Case of B 1933+503," shows that the lens galaxy must have a nearly flat rotation curve. The second, "B1359+154: A Six Image Lens Produced by a $z = 1$ Compact Group of Galaxies," explores the unique mass distribution required to produce six images of a single background source.

During the second year we have focused more closely on the relationship of baryons and dark matter. In 2 papers and a conference proceeding on "CDM Substructure" we show that the anomalous flux ratios observed in many gravitational lenses are consistent with the lens halos containing approximately 1% of their mass in massive ($10^6 M_\odot$ to $10^9 M_\odot$) satellite galaxies, as is expected in cold dark matter halo models. A short conference proceeding, "Mass Follows Light" shows that dark matter halos must be aligned with their luminous galaxies by comparing the relative alignments of lens galaxies and models for their mass distributions. A longer conference proceeding, "Dynamical Probes of the Halo Mass Function", gives a general exploration of the themes introduced by "Global Probes of the Impact of Baryons on Dark Matter Halos". "Gravitational Lenses, the Distance Ladder and the Hubble Constant: A New Dark Matter Problem" shows that the 5 lenses with simple geometries and accurately measured time delays can be reconciled with local estimates for the Hubble constant (72 ± 8 km/s Mpc) only if they have mass distributions which trace the distribution of light (i.e. constant M/L models), while models with dark matter require significantly lower Hubble constants (about 50 km/s Mpc). A nearly completed paper expands on this problem to show that CDM halo models require $50 < H_0 < 60$ and that the expected value for the Hubble constant is determined by the cold baryon fraction in the halos. "Constraints on the Long-Range Properties of Gravity from Weak Gravitational Lensing" shows that alternative theories to dark matter for explaining flat rotation curves should have obvious signatures in weak lensing experiments that are already mildly inconsistent with the data. The last paper, "Chandra Observations of the QSO Pair Q2345+007: Binary or Gravitational Lens" shows that this wide separation quasar pair must be a binary lens. There is no sign of a massive halo to produce the system as a lens in the X-rays, and the X-ray properties of the two images are inconsistent.

[1] Gravitational Lenses, the Distance Ladder and the Hubble Constant: A New Dark Matter Problem, Kochanek, C.S., 2002, ApJ, astro-ph/0204043, submitted

[2] Strong Lensing Constraints on Small-Scale Linear Power, Dalal, N., & Kochanek, C.S., 2002, PRL, astro-ph/0202290, submitted

[3] Direct Detection of CDM Substructure, Dalal, N., & Kochanek, C.S., 2001, ApJ, astro-ph/0111456, in press

[4] Chandra Observations of the QSO Pair Q2345+007: Binary or Gravitational Lens, Green, P.J., Kochanek, C.S., Sieminginowska, A., Kim, D.-W., Markevitch, M., Silverman, J., Dosaj, A., Jannuzi, B., & Smith, C., 2001, ApJ, astro-ph/0202081, in press

[5] Mass Follows Light, Kochanek, C.S., 2001, proceedings of the Yale Cosmology Workshop on the Shapes of Galaxies and Their Halos

[6] Dynamical Probes of the Halo Mass Function, Kochanek, C.S., 2001, The Dark Universe, ed., M. Livio, (Cambridge University Press: Cambridge)

[7] *Detection of CDM Substructure*, Kochanek, C.S., & Dalal, N., 2001, The Mass of Galaxies at Low and High Redshift, ed., R. Bender

[8] *Constraints on the long-range properties of gravity from weak gravitational lensing*, White, M., & Kochanek, C.S., 2001, *ApJ*, **560**, 539.

[9] *Global Probes of the Impact of Baryons on Dark Matter Halos*, Kochanek, C.S., & White, M., 2001, *ApJ*, **559**, 531.

[10] *Cusped Mass Models Of Gravitational Lenses*, Munoz, J.A., Kochanek, C.S., & Keeton, C.R., 2001, *ApJ*, **558**, 657.

[11] *B1359+154: A Six Image Lens Produced by a z = 1 Compact Group of Galaxies*, Rusin, D., Kochanek, Norbury, M., Falco, E.E., Impey, C.D., Lehar, J., McLeod, B.A., Rix, H.-W., Keeton, C.R., Munoz, J.A., & Peng, C.Y., 2001, *ApJ*, **557**, 594.

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[13] *The Importance of Einstein Rings*, Kochanek, C.S., Keeton, C.R., & McLeod, B.A., 2001, *ApJ*, **547**, 50.