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"Dark Matter in the Universe and in the Galaxy"
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PI: Marc Kamionkowski

During the past four years, Prof. Kamionkowski and collaborators have made progress in research on the nature and distribution of dark-matter in the Universe and in the Galaxy, and on related topics in astrophysics and cosmology. Funds from this NASA ATP grant have provide half-time support for 1.5 years for a postdoctoral research associate, Dr. Frank J. Summers (the other half of his support was provided by the Hayden Planetarium at the American Museum of Natural History; he is now an astrophysicist full time at the planetarium); partial support for Prof. Tsvi Piran (of the Hebrew University in Jerusalem) to visit Columbia University for the academic year 1999–1999; and partial support for several graduate students and a few undergraduate students as well. We have made progress on research on the cosmic microwave background, large-scale structure, issues related to particle dark matter, and the gamma-ray-burst enigma. Research supported at least in part by this grant has resulted during the grant period in sixty papers which have been completed, accepted for publication, and/or appeared in journals and conference proceedings. This includes the papers by Jungman et al. on cosmological-parameter determination with the CMB; the first papers on the unique polarization pattern produced by gravitational waves; a review article on supersymmetric dark matter in *Physics Reports*; a review article on the cosmic microwave background *Annual Reviews of Nuclear and Particle Science*; a review article on gamma-ray bursts in *Physics Reports*; and the theoretical prediction of a prompt optical afterglow for gamma-ray bursts that was subsequently detected by ROTSE.

Prof. Kamionkowski was awarded the 1998 Helen B. Warner Prize by the American Astronomical Society for research supported, at least in part, by this ATP grant. He has also been named a 1998 DoE Outstanding Junior Investigator. He has served as the Astrophysics Editor of *Physics Reports* and a receivinvg editor for *The Journal of High Energy Physics*. He has also served on the GLAST Facilities Science Team, on the NASA Structure and Evolution of the Universe Subcommittee, and on the Theory and Computation Panel of the Astronomy and Astrophysics Survey Committee.

Graduate students working with Prof. Kamionkowski have obtained postdoctoral positions at Princeton University (A. Refregier), the Max-Planck-Institüt fur Astrophysik (Catherine Cress), and Caltech (Ari Buchalter). An undergraduate (Ali Kinkhabwala) working with the PI was named a Finalist for the American Physical Society's 1998 Apker Award for undergraduate research and has gone on to graduate school, with an NSF Fellowship, at Princeton. Two other undergraduates, Nicolaos Toumbas and Susan Kassin, have gone on to graduate school, respectively, at Stanford University and Ohio State University.

A significant fraction of the research supported by this ATP has been on the cosmic microwave background (CMB). Prof. Kamionkowski and collaborators showed how the polarization of the CMB could be used to detect long-wavelength gravitational waves, such as those produced by inflation. With Kosowsky, Prof. Kamionkowski calculated the amplitude of a stochastic gravitational-wave background that could be detected for a satellite experiment of a given sensitivity and angular resolution. They showed that polarization should improve the sensitivity of MAP to these gravity waves, and that the Planck Surveyor should do even better. More recent work with Wang and Jaffe shows that the sensitivity to the gravitational-wave signal could be improved by a factor of 30 with a deeper survey of a smaller fraction of the sky. In related work, Prof. Kamionkowski, Caldwell, and a student (Wadley) calculated and illustrated the CMB temperature/polarization pattern produced by a single plane-wave gravitational wave. They calculated the amplitude of such a wave that would be detectable with MAP and Planck, and compared that with the sensitivity of traditional gravitational-wave detectors like LIGO and LISA. With Lue and Wang, the PI showed how parity violation from new high-energy physics could conceivably give rise to an obervable signature in the CMB polarization.

Several other ideas involving the CMB were investigated with the support of this grant. With Loeb, Prof. Kamionkowski showed how measurement of the polarization of CMB photons scattered by hot gas in a cluster could be used to determine the quadrupole moment of the CMB incident on that cluster. Prof. Kamionkowski and Jaffe calculated the amplitude of secondary anisotropies produced by scattering of CMB photons from reionized regions (the Ostriker-Vishniac effect). They showed that the amplitude of this small-angle anisotropy depends quite sensitively on the epoch of reionization. Thus, when combined with measurement of the damping of primary anisotropies (the acoustic peaks in the CMB power spectrum) this may provide a probe of the epoch of reionization If the Universe has a critical density, then temperature fluctuations are produced at the CMB surface of last scatter near a redshift $z \simeq 1100$, well beyond the redshifts accessible with galaxy surveys or diffuse cosmological backgrounds at other wavelengths. However, if the Universe does not have a critical density, then additional temperature anisotropies are produced by gravitational potential wells along the line of sight at lower redshifts. Therefore, in an open (or cosmological-constant) Universe, there will be a cross-correlation between the CMB and the x-ray background (XRB). Prof. Kamionkowski and an undergraduate student (Kinkhabwala) calculated the amplitude of this cross-correlation and used a published upper limit to show that open cold-dark-matter models (and the "open-inflation" models that produce them) with $\Omega_0 \simeq 0.3$ are untenable, unless the amplitude of fluctuations in x-ray sources are significantly smaller than that of other high-redshift sources.

Research has also been carried out on probing the large-scale distribution of mass in the Universe today, and on structure-formation theories. The PI and several collaborators investigated the possibility of determining the large-scale distribution of mass in the Universe via measurement of ellipticity-ellipticity correlations in the FIRST radio survey induced by weak gravitational lensing due to mass inhomogeneities along the line of sight. Dr. Summers, Prof. Kamionkowski, and a student (Ben Sugerman) investigated the distribution of protogalactic masses and angular momenta in an effort to understand how the luminosity function and angular-momentum distribution of disk galaxies arises from an initial power spectrum of density perturbations. To do so, a large-scale N-body and hydrodynamic simulation was carried out. They isolated galaxies at redshift zero in this simulation and then traced back the protogalaxies from which these galaxies evolved. The distribution of protogalactic masses and spins is now being compared with an analytic model. The PI and another student (Ari Buchalter) calculated both the spatial and angular three-point correlation functions expected in a variety of cold-dark-matter models.

Several projects related to the distribution and possible detection of dark matter in our Galactic halo were studied. The PI and an undergraduate student (Kinkhabwala) investigated the uncertainty in particle-dark-matter detection rates due to imprecise knowledge of the spatial and velocity distribution of WIMPs, and they showed it to be relatively small. A student (Chen) and the PI calculated some new cross sections needed for accurate predictions of rates for indirect detection of particle dark matter. A new scheme for detection of high-energy neutrinos from dark-matter annihilation and other astrophysical sources was investigated.

New schemes for learning more about gravitational-microlensing events were investigated. It was proposed that distortions to the canonical microlensing light curve could be used to determine the properties of the lens. With R. M. Rich and A. Buchalter, this idea was evaluated thoroughly with a sophisticated model of the stellar populations, mass distribution, and velocity structure of the Galactic disk and bulge. Similar calculations were carried out to evaluate the feasibility of detecting microlensing parallax from ground-based observations. These calculations were relevant for the PLANET and GMAN collaborations that subsequently arose.

The PI was involved in several projects involving the calculation of nuclear-reaction rates needed for stellar evolution and for predictions of solar-neutrino fluxes. The PI and Bahcall showed that a purported new value for the rate for the fundamental proton-proton reaction was incorrect. In related work, the PI, Bahcall, and a Chen carried out new calculations of the electron-screening correction for the proton-proton reaction. The PI was also a member of a collaboration that prepared an in-depth review article on all of the nuclear reactions needed for stellar evolution.

The grant supported public-outreach efforts through the joint appointment of Dr. Summers at Columbia University and at the Hayden Planetarium.

During his stay at Columbia University, Prof. Piran predicted that a prompt optical afterglow should accompany GRBs, and shortly thereafter, this afterglow was discovered for GRB 990123. He also participated in the discovery of jets and beamed emission in GRB 990123 and GRB 980519. A comprehensive review article on gamma-ray bursts in *Physics Reports* was completed during his visit. He also carried out research on the statistics and origin of large-scale voids in the Universe.

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