Performance Report on NASA Grant NAG 5-3085 for the period 10/15/1996–10/14/1997

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Project Title: Gas Dynamics and the Formation of Galaxies and Quasars

Below we enclose a list of papers that were written during 1995/96. These papers focus on structure formation in the universe at high redshifts, and accomplish various aspects of the research goals of this grant.

Title: Microlensing of Gamma-Ray Burst Afterglows
Authors: Abraham Loeb, Rosalba Perna (Harvard)
Comments: Submitted to ApJ Letters, astro-ph/9708159
Date: August 1997
Abstract: The afterglow of a cosmological Gamma-Ray Burst (GRB) should appear on the sky as a narrow emission ring of radius $3\times10^{16}\mathrm{cm}(t/\mathrm{day})^{5/8}$ which expands faster than light. After a day, the ring radius is comparable to the Einstein radius of a solar mass lens at a cosmological distance. Thus, microlensing by an intervening star can modify significantly the lightcurve and polarization signal from a GRB afterglow. We show that the achromatic amplification signal of the afterglow flux can be used to determine the impact parameter and expansion rate of the source in units of the Einstein radius of the lens, and probe the superluminal nature of the expansion. If the synchrotron emission from the afterglow photosphere originates from a set of coherent magnetic field patches, microlensing would induce polarization variability due to the transient magnification of the patches behind the lens. The microlensing interpretation of the flux and polarization data can be confirmed by a parallax experiment which would probe the amplification peak at different times. The fraction of microlensed afterglows can be used to calibrate the density parameter of stellar-mass objects in the Universe.

Title: Do the Electrons and Ions in X-ray Clusters Share the Same Temperature?
Authors: David Fox, Abraham Loeb
Comments: Submitted to ApJ, astro-ph/9706266
Date: June 1997
Abstract: The virialization shock around an X-ray cluster primarily heats the ions, since they carry most of the kinetic energy of the infalling gas. Subsequently, the ions share their thermal energy with the electrons through Coulomb collisions. We quantify the expected temperature difference between the electrons and ions as a function of radius and time, based on a spherical self-similar model for the accretion of gas by a cluster in an Omega=1, h=0.5 universe. Clusters with X-ray temperatures $T=(4-10)*10^7$ K, show noticeable differences between their electron and ion temperatures at radii >2 Mpc. Hich resolution spectroscopy with future X-ray satellites such as Astro E may be able to determine the ion temperature in intracluster gas from the width of its X-ray emission lines, and compare it to the electron temperture as inferred from the free-free emission spectrum. Any difference between these temperatures can be used to date the period of time that has passed since the infalling gas joined the cluster.

Title: Probing The Mass Fraction of MACHOs in Extragalactic Halos
Authors: Rosalba Perna, Abraham Loeb
Comments: Submitted to ApJ Letters, astro-ph/9706119
Date: June 1997
Abstract: Current microlensing searches calibrate the mass fraction of the milky Way halo which is in the form of Massive Compact Halo Objects (MACHOs). We show that surveys like the Sloan Digital Sky Survey (SDSS) can probe the same quantity in halos of distant galaxies. Microlensing of background quasars by MACHOs in intervening galaxies would distort the equivalent width distribution of the quasar emission lines by an amplitude that depnds on the projected quasar-galaxy separation. For a statistical sample of detectable at the >2sigma level out to a quasar-galaxy impact parameter of several tens of kpc, as long as extragalactic halos are made of MACHOs. Detection of this signal would test whether the MACHO fraction inferred for the Milky-Way halo is typical of other galaxies.

Title: Effects of Dust on Gravitational Lensing by Spiral Galaxies
Authors: Rosalba Perna, Abraham Loeb, Matthias Bartelmann
Comments: ApJ, in press, astro-ph/9705172
Date: May 1997
Abstract: Gravitational lensing of an optical QSO by a spiral galaxy is often counteracted by dust obscuration, since the line-of-sight to the QSO passes close to the center of the galactic disk. The dust in the lens is likely to be correlated with neutral hydrogen, which in turn should leave a Lyman-alpha absorption signature on the QSO spectrum. We use the estimated dust-to-gas ratio of the Milky-Way galaxy as a mean and allow a spread in its values to calculate the effects of dust on lensing by low redshift sprial galaxies. Using a no-evolution model for spirals at Z<1 we find (in Lambda=0

cosmologies) that the magnication bias due to lensing is stronger than dust obscuration for QSO samples with a magnitude limit B<16. The density parameter of netural hydrogen, Omega_HI, is overestimated in such samples and is underestimated for fainter QSOs.

Title: Detection of the First Star Clusters with NGST
Authors: Zoltan Haiman, Abraham Loeb
Comments: To appear in the Proceedings of Science with the Next Generation Space Telescope, 7-9 April, 1997, astro-ph/9705144
Date: May 1997
Abstract: We calculate the observable signatures of the first generation of stars at high redshift (5<z<100). To determine the cosmic star-formation history, we use an extension of the Press-Schechter formalism for Cold Dark Matter (CDM) cosmologies that inorporates gas pressure. We calibrate the fraction of gas converted into stars to be 6% so as to reproduce the 1% solar C/H ratio observed in the intergalactic medium (IGM) at z=3. With this star-formation efficiency, we find that NGST would be able to image more than 10^4 star clusters from high redshifts (z>10) within its 4'x4' field of view. If stars occupy a region comparable to the virial radius of the cluster, then 1% of these clusters could be resolved. We calculate the expected number-flux relation and angular size distribution for these early star clusters. We also describe the reionization of the IGM due to the first generation of stars, and the consequent damping of the CMB anisotropies on small angular scales. This damping could be detected below 10 degree angular scales by MAP and PLANCK.

Title: The First Stars and Quasars in the Universe
Author: Abraham Loeb
Comments: Invited contribution to 'Science with The Next Generation Space Telescope', Greenbelt, April 1997, astro-ph/9704290
Date: April 1997
Abstract: The transition between the nearly smooth initial state of the Universe and its clumpy state today occurred during the epoch when the first stars and low-luminosity quasars formed. For Cold Dark Matter cosmologies, the radiation produced by the first baryonic objects is expected to ionize the Universe at z=10-20 and consequently suppress by 10% the amplitude of microwave anisotropies on angular scales <10 degrees. Future microwave anisotropy satellites will be able to detect this signature. The production and mixing of metals by an early population of stars provides a natural explanation to the metallicity, ~1% solar, found in the intergalactic medium at redshifts z<5. The Next Generation Space Telescope (NGST) will be able to image directly the ''first light'' from these stars. With its nJy sensitivity, NGST is expected to detect >10^3 star clusters per square arcminute at z>10. The brightest sources, however, might be early quasars. The infrared flux from Jane Eddington luminosity, 10^6 solar mass, black hole at z=10 is 10 nJy at 1 micron, easily detectable with NGST. The time it takes a black hole with a radiative efficiency of 10% to double its mass amounts to more than a tenth of the Hubble time at z=10, and so a fair fraction of all systems which harbor a central black hole at this redshift would appear active. The redhift of all sources can be determined from the Lyman-limit break in their spectrum, which overlaps with the NGST wavelength regime, 1-3.5 micron, for 10<z<35. Absorption spectra of the first generation of star clusters or quasars would reveal the reionization history of the Universe. The intergalactic medium might show a singificant opacity to infrared sources at z>10 due to dust produced by the first supernovae.

Title: Signatures of Intergalactic Dust from the First Supernovae
Authors: Abraham Loeb, Zoltan Haiman
Comments: ApJ, in press, 12/1/97 issue, astro-ph/9704133
Date: April 1997
Abstract: We quantify the consequences of intergalactic dust produced by the first Type II supernovae in the Universe. The fraction of gas converted into stars is calibrated based on the observed C/H ratio in the intergalactic medium at z=3, assuming a Scalo mass function for the stars. The associated dust absorbs starlight energy and emits it at longer wavelengths. For a uniform mix of metals and dust with the intergalactic gas, we find that the dust distorts the microwave background spectrum by a y-parameter in the range (0.02-2)x10^{-5}(M_d/0.3M-sun), where M_d is the average mass of dust produced per spuernova. The opacity of intergalactic dust to infrared sources at redshifts z>10 is significant, tau=(0.1-1)x(M_d/0.3M_sun), and could be detected with the Next Generation Space Telescope. Although dust suppresses

the Ly-alpha emission from early sources, the redshifts of star clusters at z=10-35 can be easily inferred from the Lyman-limit break in their infrared spectrum between 1-3.5 micron.

Title: Getting Around Cosmic Variance
Authors: Marc Kamionkowski, Abraham Loeb
Comments: astro-ph/9703118
Date: March 1997
Abstract: Cosmic microwave background (CMB) anisotropies probe the primordial density field at the edge of the observable Universe. There is a limiting precision (``cosmic variance'') with which anisotropies can determine the amplitude of primordial mass fluctuations. This arises because the surface of last scatter (SLS) probes only a finite two-dimensional slice of the Universe. Probing other SLSs observed from different locations in the Universe would reduce the cosmic variance. In particular, the polarization of CMB photons scattered by the electron gas in a cluster of galaxies provides a measurement of the CMB quadrupole moment seen by the cluster. Therefore, CMB polarization measurements toward many clusters would probe the anisotropy on a variety of SLSs within the observable Universe, and hence reduce the cosmic-variance uncertainty.

Title: Optical Appearance of the Debris of a Star Disrupted by a Massive Black Hole
Authors: Abraham Loeb, Andrew Ulmer
Comments: Submitted to ApJ, astro-ph/9703079
Date: March 1997
Abstract: We show that the dsiruption of a star by a 10^6 solar mass black hole in a galactic nucleus could under favorable circumstances produce an optically-thick envelope that radiates with a thermal spectrum at the Eddington limit, 10^4 K, would be easily detectable in optical surveys. If most galaxies harbor a massive black hole at their center, then the Sloan Digital Sky Survey might find hundreds of galaxies with nuclear activity of this type. Because the envelope is driven to shine near the Eddington limit, a measurement of the source redshift and total lumniosity could yield the black hole mass.

Title: Constraints on Galaxy Evolution and the Cosmological Constant From Damped Ly-alpha Absorbers
Authors: Eric Woods, Abraham Loeb
Comments: Submitted to ApJ, astro-ph/9703076
Date: March 1997
Abstract: We use the existing catalog of Damped Lyman-Alpha (DLA) systems to place constraints on the amount of evolution in the baryonic content of galaxies and on the value of the cosmological constant. The density of cold gas at redshifts z=3+-1 is obtained from the mean HI column density of DLAs per cosmological path length. This path length per unit redshift is in turn a sensitive function of the vacuum density parameter, Omega_v. We compare the total inferred mass of cold gas at high redshifts to that observed in stars today for flat cosmologies. We define ``eta'' to be net fraction of the baryonic content of local galaxies which was expelled since z=3, and use Bayesian inference to derive confidence regions in the (eta, Omega_v) plane. In all cosmologies we find that eta <0.4 with at least 95% confidence if <25% of the current stellar population formed before z=3. The most likely value of eta is negative, implying a net increase by several tens of percent in the baryonic mass of galaxies since z=3+-1. On the other hand, recent observations of high metal abundances in the intracluster medium of rich clusters (Loewenstein & Mushotzky 1996) require that metal-rich gas be expelled from galaxies in an amount approximately equal to the current mass in stars. Based on our results and the low metallicty observed in DLAs at z>2, we infer that more than half of the baryonic mass processed through galaxies must have been assembled and partly expelled from galaxies after z=2. We expect our constraints to improve considerably as the size of the DLA sample will increase with the forthcoming Sloan Digital Sky Survey.

Title: Microlensing of an Elliptical Source by a Point Mass
Authors: David Heyrovsky, Abraham Loeb
Comments: To appear in ApJ, November 1997, astro-ph/9702097
Date: February 1997
Abstract: We present an efficient method for computing lightcurves of an elliptical source which is microlensed by a point mass. The amplification of

an exteneded source invovles a two-dimensional integral over its surface brightness distribution. We show that for a general surface brightenss profile with an elliptical symmetry, this integral can be reduced to one dimension. We derive analytical results for the entire lightcurve in the limit of low (e.g. planetary) mass lenses, and for the wings of all microlensing lightcurves in general. In both cases, the lightcurve carries information about deviations of the source from elliptical symmetry, e.g. due to spots. The method is ued to find the amplification of a circular red giant photosphere and an inclined accretion disk. We demonstrate that microlensing of an emission line from a disk can be used to infer the disk velocity structure and surface brightness profile.

Title: Formation and Signaturs of the First Stars
Authors: Zoltan Haiman, Abraham Loeb
Comments: To appear in the Proceedings of the 18th Texas Symposium on Relativisitic Astrophysics, Chicago, December 1996, eds. A. Olinto, J. Frieman and D. Schramm, (World Scientific), astro-ph/9701239
Date: January 1997
Abstract: We use a spherical hydrodynamics code to show that in cold dark matter cosmologies, the first stars form at z=50 through the direct collapse of gas in low-mass systems (approx 10^4 solar masses). Photons from the first stars easily photodissociate the molecular hydrogen throughout the universe and so molecular cooling does not affect the subsequent fragmentation of gas clouds into stars. We examine observable signatures of the pre-galactic population of stars. These include the detected metallicity and photo-ionization of the intergalactic medium, and the soon to be detected damping of microwave anisotropies on small angular scales (<10 degrees). The Next Generation Space Telescope will be able to directly image the pre-galactic star clusters, while the DIMES experiment could detect their Bremsstrahlung emission.

Title: Microlensing of Quasars by Stars in Their Damped Lyman-alpha Absorbers
Authors: Rosalba Perna, Abraham Loeb
Comments: To appear in ApJ, astro-ph/9701226
Date: January 1997
Abstract: The damped Lyman alpha absorbers (DLAs) in quasar spectra are believed to be the progenitors of present-day galaxies. We examine the probability for microlensing of background quasars by stars in their DLAs. Microlensing by an individual star should magnify the continuum but not the broad emission lines of the quasars. Consequently, the equivalent width distribution of microlensed quars would be distorted. We model a representative spiral galaxy as a closed system composed of a bulge, a disk, and a halo, and evolve the mass fraction of stars in the disk based on the observed metallicity of DLAs at high redshifts. The microlensing signatures are stronger if the halo of the galaxy is made of Massive Compact Halo Objects (MACHOs). In this case, the distortion imprinted by microlensing on the equivalent width distribution of quasar emission lines can be detected with high significance in a sample of about 10 DLAs with HI column densities N>10^21 cm^-2 and absorption redshifts z_abs<1. About a tenth of all quasars with DLAs (N>10^20 cm^-2) might show excess variability on timescales shorter than five years. A search for these signals would complement microlensing searches in local galaxies and calibrate the MACHO mass fraction in galactic halos at high redshifts.

Title: Gravitational Lensing of Quasars by Spiral Galaxies
Author: Abraham Loeb
Comments: Contribution to Texas symposium 1996, astro-ph/9701100
Date: January 1997
Abstract: Gravitational lensing by a spiral galaxy occurs when the line-of-sight to a background quasar passes within a few kpc from the center of the galactic disk. Since galactic disks are rich in neutral hyrdrogen, the quasar spectrum will likely be marked by a damped Lyman-alpha absorption through at the lens redshift. Therefore, the efficiency of searches for gravitational lensing with sub-arcsecond splitting can be enhanced by 1-2 orders of magnitude by focusing on a subset of all bright quasars which show low-redshift (z<1) strong Lyman-alpha absorption (N>10^{21} cm^{-2}). The double-image signature of lensing could, in principle, be identified spectroscopically and without the need for high-resolution imaging. The absorption spectrum of a spiral lens would show a generic doubnle-step profile due to the superposition of the two absorption troughs of the different

images. Finally, we note that searches for microlensing signatures of quasars with damped Lyman-alpha absorption coud calibrate the fraction of MACHOs in galactic halos at high redshift.

Title: Signatures of Stellar Reionization of the Universe
Authors: Zoltan Haiman, Abraham Loeb
Comments: ApJ, 483, 21 (1997), astro-ph/9611028
Date: November 1996
Abstract: The high ionization level and universal metallicity (1% solar) of the intergalactic gas at redshifts z<5 implies that nonlinear structure had started to form in the universe at earlier times than we currently probe. In Cold Dark Matter (CDM) cosmologies, the first generation of baryonic objects emerges at redshifts z=10-50. Here we examine the observable consequences of the possibility that an early generation of stars reionized the Universe and resulted in the observed metallicty of the Lyman-alpha forest. Forthcoming microwave anisotropy experiments will be sensitive to the damping of anisotropies caused by scattering off free electrons from the reionization epoch. For a large range of CDM models with a Scalo stellar mass function, we find that reionization occurs at a redshift z>10 degrees by a detectable amount, of order 10-25%. However, reionization is substantially delayed if the initial stellar mass function transformed most of the baryons into low mass stars. In this case, the mass fraction of pre-galactic stars could be constrained from the statistics of microlensing events in galactic halos or along lines of sight to quasars. Deep infrared imaging with future space telescopes (such as SIRTF or the Next Generation Space Telescope) will be able to detect bright star clusters at z>5. The cumulative Bremsstrahlung emission from these star clusters yields a measurable distortion to the spectrum of the microwave background.

Title: Gravitational Lensing of the X-Ray Background by Clusters of Galaxies
Authors: Alexandre Refregier, Abraham Loeb
Comments: ApJ, 478, 476 (1997), astro-ph/9610248
Date: October 1996
Abstract: Gravitational lensing by clusters of galaxies affects the cosmic X-ray background (XRB) by altering the observed density and flux distribution of background X-ray sources. At faint detection flux thresholds, the resolved X-ray sources appear brighter and diluted, while the unresolved component of the XRB appears dimmer and more anisotropic, due to lensing. The diffuse X-ray intensity in the outer halos of clusters might be lower than the sky-averaged XRB, after the subtraction of resolved sources. Detection of the lensing signal with a wide-field X-ray telescope could probe the mass distribution of a cluster out to its virialization boundary. In particular, we show that the lensing signature imprinted on the resolved component of the XRB by the cluster A1689, should be difficult but possible to detect out to 8' at the 2-4 sigma level, after 10^6 seconds of observation with the forthcoming AXAF satellite. The lensing signal is fairly insensitive to the lens redshift in the range 0.1<z<0.6. The amplitude of the lensing signal is however sensitive to the faint end slope of the number-flux relation for unresolved X-ray sources, and can thus help constrain models of the XRB. A search for X-ray arcs or arclets could identify the fraction of all faint sources which originate from extended emission of distant galaxies. The probability for a 3 sigma detection of an arclet which is stretched by a factor of about 3 after a 10^6 seconds observation of A1689 with AXAF, is roughly comparable to the fraction of all background X-ray sources that have an intrinsic size of order 1''.

Title: Effect of Gravitational Lensing on Measurements of the Sunyaev-Zel'dovich Effect
Authors: Abraham Loeb, Alexandre Refregier
Comments: ApJ Letters, 476, 59 (1997), astro-ph/9610048
Date: October 1996
Abstract: The Sunyaev-Zel'dovich (SZ) effect of a cluster of galaxies is usually measured after background radio sources are removed from the cluster field. Gravitational lensing by the cluster potential leads to a systematic deficit in the residual intensity of unresolved sources behind the cluster core relative to a control field far fom the cluster center. As a result, the measured decrement in the Rayleigh-Jeans temperature of the cosmic microwave backgoround is overestimated. We calculate the associated systematic bias which is inevitably introduced into measurements of the Hubble constant using the SZ effect. For the cluster A2218, we find that observations at 15 GHz with

a beam radius of 0'.4 and a source removal threshold of 100 microJy underestimate the Hubble constant by 6-10%. If the profile of the gas pressure declines more steeply with radius than that of the dark matter density, then the ratio of lensing to SZ decrements increases towards the outer part of the cluster.

Title: Destruction of Molecular Hydrogen During Cosmological Reionization
Authors: Zoltan Haiman, Martin Rees, Abraham Loeb
Comments: ApJ, 476, 458 (1997), astro-ph/9608130
Date: August 1996
Abstract: We investigate the ability of primordial gas clouds to retain molecular hydrogen (H_2) during the initial phase of the reionization epoch. We find that before the Stromgren spheres of the individual ionizing sources overlap, the UV background below the ionization threshold is able to penetrate large clouds and suppress their H_2 abundance. The consequent lack of H_2 cooling could prevent the collapse and fragmentation of clouds with virial temperatures T_vir<10^4 K (or masses 10^8 Msun [(1+z_vir)/10]^{-3/2}). This negative feedback on structure-formation arises from the very first ionizing sources, and precedes the feedback due to the photoionization heating.