Cosmic Microwave Background Radiation, Clusters of Galaxies, and COSMOLOGY

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CLUSTERS OF GALAXIES
Thousands of galaxies with $v \sim 1000$ km/s

Hot intergalactic gas with $T_e \sim 3 – 10$ KeV

Gravitational potential defined by invisible *dark matter*

Much *more distant* galaxies are gravitationally *lensed* by A 2218
Electron temperature ~ 9 KeV

Electron density ~ 0.03 cm⁻³

Dark matter mass – up to $10^{15}$ Msun

Msun = 2 $10^{33}$ g

Sound velocity of gas is close to velocities of galaxies
Why we should lose time for clusters during Landau100 conference?

Isaak Khalatnikov. Recent book of reminiscences.

Lev Landau was involved into Soviet program of atomic and hydrogen bomb.

Kompaneets, 1956, JETP paper: Lev Landau, Israil Gelfand, Sergey Dyakov are mentioned. They were helping Yakov Zeldovich group to solve Kompaneets equation and to find an upper limit for the temperature of gas during explosion.

\[ \frac{\partial n}{\partial y} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left( n + n^2 + \frac{\partial n}{\partial x} \right) \]
Fokker-Planck expansion of the kinetic equation with induced scattering term yields

\[
\frac{\partial n}{\partial y} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left( n + n^2 + \frac{\partial n}{\partial x} \right)
\]

\[n = \frac{c^2 I_e}{8\pi \hbar \nu^3}\]  
- occupation number, \(I\) – radiation intensity

\[x = \frac{\hbar \nu}{kT_e}\]  
- photon frequency,

\[y = \frac{kT_e}{m_e c^2} \sigma_T N_e c t = \frac{kT_e}{m_e c^2} u\]  
- time and number of scatterings

Kompaneets equation describes interaction of a radiation field with free hot maxwellian electrons due to Compton scattering. The energy exchange due to Doppler effect and recoil.

Beautiful physics behind the term \(\sim n^2\) describing induced Compton scattering
Kompaneets equation was published in 1956 because it occurred useless for weapon research.

However!!! Comptonization process described by this equation defines:

- a) the radiation spectra of accretion disks around black holes
- b) the interaction of matter and radiation in the early universe
- c) the diminution of Cosmic Microwave Background Radiation brightness toward clusters of galaxies with hot gas

Great applications in modern cosmology and high energy astrophysics !!!
Microwave Sky seen by WMAP spacecraft

Dark blue -200 microK
Dark blue -200 microK
Red +200 microK

CMB (Cosmic Microwave Background) - practically isotropic and has a black spectrum. Tiny !!! primordial angular fluctuations are of interest.
Fig. 2. The scattering of isotropic radiation field by the cloud of electrons.

Cloud is invisible
SCATTERING OF RADIATION BY HOT MAXWELLIAN ELECTRONS

Spectral changes due to doppler-effect on moving electrons with $kT_e \sim 5$ KeV and average velocity of the order of $1/7 \, c$

Line is broadened and effectively shifted toward higher frequencies due to second order effects in $v/c$. 

$\frac{\nu}{\nu_0}$

$\frac{kT_e}{kT_e}$

$y = 0.15$

$x = \frac{kT_e}{kT_e}$

black body

laser line
Initial photons have low frequency, electrons are very hot, only Doppler effect is of importance.

High frequency wing of the line after scattering is stronger than the low frequency one! Cusp due to scatterings to small angles! This is the kernel of Integral kinetic equation.

Every photon in the black body spectrum with $T_r \ll T_e$ also moves towards higher frequencies. As a result – intensity drops in the Rayleigh-Jeans part of the spectrum and increases in the Wien part!!!

In centimeter spectral band clusters should be observed as a holes in the sky average brightness defined by CMB intensity. The depth of this hole does not depend on the redshift of the cluster of galaxies. It depends only on temperature of the electrons and optical depth of the cluster.
The spectrum of clusters due to thermal effect

\[ x = \frac{h \nu}{k T_c} \]

The microwave spectrum of the cluster depends only on

\[ x = \frac{h \nu}{k T_c} \]

and is independent on redshift \( z \) of the cluster because both nominator and denominator of \( x \) are proportional to \((1 + z)\)
Interferometric observations of clusters

Carlstrom et al.
X-Ray brightness of clusters decreases with redshift as $(1+z)^4$

SZ-brightness does not depend on redshift!

Cluster at $z = 0.888$ is as bright as cluster at $z=0.17$

We are able to observe all existing clusters in the whole Universe
New spacecraft (PLANCK Surveyor) and ground-based telescopes are going to observe CMB brightness diminution in the directions towards rich clusters of galaxies and to look for them on the black sky.

Main goal – to check what was the growth rate of clusters of galaxies (how their density was increasing with time) and the search for barionic oscillations in their spatial distribution.

These experiments should open new way to estimate key cosmological parameters including the equation of state of the dark energy.
Atacama Cosmology Telescope, 5200 m height, 3024 bolometers,

Site of South Pole Telescope
Now 10m telescope is staying there
2800 m altitude
980 bolometers

AMI, Cambridge

SZ Array, California
Deep counts of galaxy clusters using thermal SZ-effect

Additional way to get information about dark matter, dark energy and other parameters of the Universe

Hundred fifty thousand clusters on the whole sky
Predicted source counts of clusters as function of $z$ for South Pole Telescope (Mohr et al) will demonstrate growth curve of clusters.

New way to investigate properties of dark energy including its equation of state.
CMB is isotropic only in one reference frame.

Motion of Solar System leads to the DIPOLE COMPONENT in the CMB brightness distribution over the SKY.

Sky is 0.1% brighter in the direction of our motion of 327 km/s and is less bright in opposite direction.

This is the brightest anisotropy on CMB sky – thousands times stronger than primordial fluctuations, main calibrator for CMB experiments.
CMB is isotropic only in one coordinate frame

Solar system is moving relative to this frame

we see anisotropy of CMB and measure our velocity

370 km/sec
Kinetic SZ-effect

\[ \frac{\Delta T_{\text{rad}}}{T_{\text{rad}}} \approx -\tau_{e} \frac{v_{z}}{c} \]

\[ F_{i}, \text{ mJy/min}^2 \]

\[ \nu, 10^{\text{Hz}} \]

\[ \lambda, \text{ mm} \]
Perculiar velocity

$V = 415 \pm 920/-760 \text{ km/s}$
Cluster MS1054 at redshift $z=0.826$ moving from us due to Universe expansion with a velocity 54% of speed of light (162 000 km/s).

SuZIE observations show that the peculiar velocity of this cluster is less than 1000 km/s with respect to the reference frame in which the cosmic background radiation is isotropic.

However its peculiar velocity is less than 1000 km/s with respect to the reference frame in which the cosmic background radiation is isotropic.
ACOUSTIC PEAKS

and

their ORIGIN
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CMB (Cosmic Microwave Background) - practically isotropic and has a black spectrum. Tiny !!! primordial angular fluctuations are of interest.
Evolution of density perturbations in the expanding Universe (Sunyaev, Zeldovich, 1970)
CMB angular distribution remembers these oscillations

*in the radiation dominated fluid*

*with barions and electrons*

After recombination photons are free and bring us information about these acoustic waves

Sloan Digital Sky Survey observes barionic oscillations in the distribution of elliptical galaxies

Dependence of the amplitude of the density perturbations on the scale

Sunyaev and Zeldovich, 1970
Acoustic peaks

Hu and Silk included crucial Dark Matter effects

Sunyaev and Zeldovich, 1970; Peebles and Yu – prediction

Boomerang, Maxima, WMAP, ACBAR, VSA, CBI - Discovery
Accreting black holes and neutron stars

Gas in the accretion disks and boundary layer is very hot ($kT_e \sim 1 – 100$ KeV) due to enormous gravitational energy release.

Main plasma cooling mechanisms is again comptonization – the scattering of low frequency seed photons on extremely hot electrons.

Exact solution of Kompaneets equation in the plasma cloud (Sunyaev, Titarchuk, 1980) demonstrates how the observed power law X-Ray spectra with exponential high energy cutoff form in accretion disks.
Exact solution of Kompaneets equation in the plasma cloud (Sunyaev, Titarchuk, 1980) demonstrates how the \textit{power law spectra with exponential high energy cutoff form} due to Comptonization.

Such X-Ray spectra are observed now from \textit{hundreds of Galactic binary X-Ray sources} – accreting neutron and black holes and from \textit{hundreds active galactic nuclei} – supermassive black holes powered by accretion.
In 2012 Russia is planning to launch SPECTRUM-X spacecraft (with telescopes designed in broad international cooperation) able to map whole sky and detect all rich clusters of galaxies in the observable Universe (≈ 150,000) and 3–5 millions AGNs (active galactic nuclei) via their X-Ray emission.

Planned microwave and X-Ray observations of clusters of galaxies should give a lot of unique cosmological information about the properties of our Universe.

In all these objects Comptonization is playing crucial role. It was first considered in early 50ties by Aleksandr Kompaneets, Yakov Zeldovich, Lev Landau and Israil Gelfand for completely different applications.