NEUTRINO MASS AND GALAXY FORMATION

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The adiabatic theory of galaxy formation in neutrino-dominated universes is reviewed. Collisionless damping leads to a density fluctuation spectrum with a cutoff, the nonlinear evolution of which naturally results in the formation of pancakes, strings and voids.

INTRODUCTION

The concensus of the observational papers presented in this volume (see for example Oort, Chincarini and Einasto) is that the structure of the universe is dominated by distinctive large scale features: superclusters, with lengths of order 25-100 Mpc, that are often more string-like than sheet-like. Rather than being isolated, there are hints of a network structure to the superclusters with large voids almost free of galaxies in between. The announcement of Lubimov et al. (1980), that their experiment on the beta decay of tritium indicates the mass of the electron neutrino lies in the range 16 eV $< m_\nu <$46 eV was in large part responsible for the resurgence of interest in the neutrino-dominated universe. In this paper we review how the presently observed distribution of galaxies may arise if the neutrino is endowed with a rest mass of order 10-100 eV.

Gershtein and Zeldovich (1966) first suggested that even a small neutrino mass may have important cosmological consequences, by contributing a larger fraction of the overall density of the universe than baryons. Marx and Szalay (1972), Cowsik and McClelland (1972) and Schramm and Steigman (1981) have refined their arguments: the present limits on the Hubble constant and the deceleration parameter of the universe result in an upper bound to the sum of the neutrino masses: $\Sigma m_\nu < 100$ eV. Calculations of the primordial He and D abundance indicate baryons can only contribute a small fraction of the critical density. The likely value of the baryon density parameter at the time of primordial nucleosynthesis lies in the range of $0.01<\Omega_B< 0.1$ (Olive et al. 1981). This suggests that if baryons dominate the mass density then the universe

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is open by a wide margin. In such a universe the growth of the initially adiabatic fluctuations is highly suppressed,as we shall see later: the presence of nonlinear structure now is incompatible with the tight upper bounds on small scale density perturbations arising from observations of microwave background temperature fluctuations, and effectively rules out such a case. Szalay and Marx (1976) first noted that the way fluctuations behave is quite different in a neutrino-dominated universe than in a baryon-dominated one. Below $T\sim1$ MeV neutrinos are collisionless particles and are thus not affected by radiation drag as ordinary matter is. This enables much larger fluctuation growth to occur, without strongly influencing the microwave background. On the other hand, neutrinos are subject to phase mixing of their orbits,which results in a characteristic Jeans mass scale corresponding to superclusters, as was realized by many authors recently (Doroshkevich et al. 1980abc, Klinkhamer and Norman 1981, Bond et al. 1980, Sato and Takahara 1980). The collapse of such systems was shown by Zeldovich (1970) to lead to highly anisotropic structures, the pancakes. These are not isolated: a cellular structure would form with huge voids in between; filaments would appear at the intersection lines of pancakes. The neutrino mass explains this structure in a simple and elegant way, as we now detail.

LINEAR PERTURBATIONS IN A NEUTRINO DOMINATED UNIVERSE

Small fluctuations may emerge naturally near the big bang itself. In the presently popular grand unified theories of particle physics the most important fluctuations are those which preserve the baryon/photon ratio, namely the adiabatic ones. These fluctuations are presumed to have a smooth scale free spectrum existing over a wide range of mass scales. As the expansion proceeds, larger and larger masses come within the horizon. There are two competing effects: gravity attracts the particles towards the highest densities, while the pressure due to thermal motion tries to prevent this. On large scales gravity always wins, matter condenses in some regions, and is rarefied in others. On small scales pressure is more important. The perturbations behave like acoustic waves; excess density is accompanied by excess pressure, and the local density oscillates.

Until the temperature has dropped to a few thousand degrees, the radiation is still sufficiently energetic to keep the matter ionized. The growth of baryon fluctuations by gravitational instability is inhibited in the ionized phase because the radiation provides a strong source of viscosity. The radiation is scattered mostly by free electrons, so once the electrons recombine into H atoms, radiation streams independently of the matter. There is no longer any resistance to fluctuation growth, and gravitational instability proceeds. This happens at a relatively late stage, at $z\sim1000$. During recombination the smallest scale fluctuations are subject to viscous damping (Silk 1968). The compressed radiation tends to diffuse and thereby smooth out all baryon fluctuations below $\sim10^{13}-10^{15}\ M_\odot$.

Even when pressure becomes negligible, the rate of fluctuation growth is small in low density universes for redshifts $<\Omega^{-1}$, when the curvature dominates the expansion. This can lead to a total growth

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factor from decoupling to today as small as 15, to be compared with the total growth of 1000 if $\Omega=1$. Since the photons were not scattered after decoupling, the present value of the temperature fluctuations of the CBR reflects the amplitude of the baryon density perturbations at that epoch. Upper limits on small scale fluctuations, such as given by Davies in this volume (10′ corresponds to $\sim 10^{15}$ $M_\odot$) implies growth by even that factor of 1000 will not be enough to give nonlinear structure by now in baryon-dominated universes.

As Doroshkevich et al. (1980a) and Bond et al. (1980) emphasized, one of the principle triumphs of a universe dominated by neutrinos or other weakly interacting particles such as gravitinos or photinos is that they can beautifully sidestep this difficulty. This occurs for two reasons. Firstly, Ω can be larger, hence the curvature-dominated era, if it exists at all, will have occured for a much shorter time. More importantly, once neutrinos become non-relativistic, which occurs before recombination, their fluctuations become gravitationally unstable on sub-horizon scales, as long as these scales are above the instantaneous value of the neutrino Jeans mass. Consequently, the amplitude of the neutrino density fluctuations greatly exceeds those of the baryon perturbations by recombination. Once decoupling occurs, the baryon fluctuations experience an accelerated growth until they equal the neutrino fluctuations. This new feature implies one can get nonlinearity occuring at $z \sim 5$, and still have the induced temperature fluctuations just smaller than the upper limits on small scales. Though safely lower than the upper bounds set by observers so far, the $\Delta T/T$ structure on all scales larger than $\sim 10'$ is predicted to be rich on the 10^{-5} to 10^{-4} level in a neutrino-dominated universe.

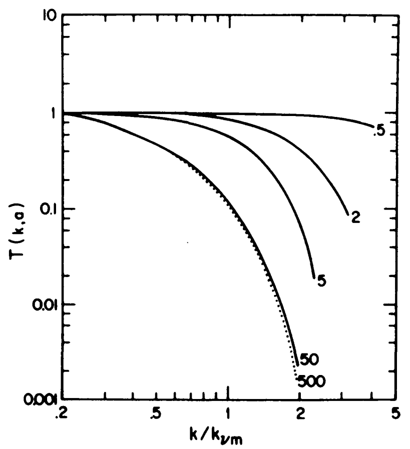

Figure 1. The transfer function of neutrino fluctuations (see text).

The occurrence of a damping cutoff in the neutrino fluctuation spectrum determines the nature of large scale structure formation in neutrino-dominated universes. Since momentum suffers the cosmological redshift, once neutrinos go nonrelativistic their velocity slows from the speed of light down to a present rms value of 6 km/s (30 eV/m_ν). The total comoving displacement the typical freely streaming neutrino traverses converges to a finite time-independent value given by the mass scale $\sim 0.5\, M_{\nu m}$ (Bond and Szalay 1982), where the damping scale is the maximum value the neutrino Jeans mass attains,

$$M_{\nu m} = 2\, m_p^{\,3}\, m_\nu^{\,-2} = 3 \times 10^{15} \;(30 \text{ eV}/m_\nu)^2\, M_\odot$$

(Bond et al. 1980, Bisnovaty-Kogan and Novikov 1980, Doroshkevich et al.

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1980c). Below this scale orbits of neutrinos streaming in different directions and/or with different speeds phase mix, effectively erasing any inhomogeneities initially present. Doroshkevich et al.(1980a) and Wasserman (1982) give a quantitative discussion of this limiting regime. Above this scale, neutrinos cannot move from one lump to another, and the self-gravity of compressions cause them to grow in magnitude via the usual Jeans instability. Bond and Szalay (1981, 1982) and Peebles (1982) have numerically integrated the coupled Einstein-Boltzmann equations to determine the detailed shape of the fluctuation spectra, which ties together these two regimes. The temporal evolution of the transfer function (amplitude of neutrino perturbations normalized to a fluctuation with mass much above the critical scale) is illustrated in Fig.1., taken from Bond and Szalay (1982). The scale factor has a=1 when the neutrinos just become nonrelativistic. It is apparent that most damping occurs between a=0.5 and a=50, which is near recombination, after which the spectral shape down to $\ll M_{\nu m}$ is frozen in.

NONLINEAR STRUCTURE IN THE UNIVERSE

Once the first mass scale in a spectrum with a damping cutoff such as that obtained from Fig.1. reaches nonlinearity, neutrino trajectories cease expanding away from each other and begin converging, resulting in the temporary formation of caustics. Just as in elasticity, we can envisage this behaviour by considering a cubical volume smaller than the damping scale. The cube suffers deformation due to the particle motion with contractions occuring along some axes, expansions along others. A spherically symmetric contraction is a special, highly degenerate case. Generally, the distribution of deformations in each of the principal directions favours asymmetry (Doroshkevich 1970). Gravitational attraction further amplifies this strain, and a highly flattened quadrangle which is still expanding or mildly contracting in the other directions results. The mass inside the cube is preserved, so when both the thickness and the volume of the cube approaches zero, its density becomes very high and a flat 'pancake' is formed, as was originally suggested by Zeldovich (1970). At first they form at isolated spots where the initial velocity perturbations had the largest gradient. Soon these regions grow, turning into huge thin surfaces which intersect, tilt and form the walls of a cell-structure which is itself unstable gravitationally. The universe may be at this cellular stage today as detailed numerical calculations indicate.

In the nonlinear phase, mode-mode coupling among Fourier components sends power to short wavelengths, and correlates phases even though the initial fluctuation spectrum may have had random phases. The evolution of structure is then best calculated in real space. As Shandarin discusses in this volume, Arnold, Zeldovich and Shandarin (1982) have applied the methods of catastrophe theory to analyze structure that develops in potential motion, i.e. with no vorticity, which, if present, should be small by the end of the linear phase anyway. They found that the two-dimensional pancakes are only the lowest order singularities, and one-dimensional strings (superclusters?) and zero-dimensional points (rich clusters?) should also appear. These features can be seen in the

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N-body simulations of Doroshkevich et al. (1980d), Melott (1982), Clypin and Shandarin (1982), Frenk et al. (1982).

When the intersection of trajectories takes place, gas pressure builds up, the velocity of the collapsing gas exceeds the speed of sound, and a shock wave is formed (Sunyaev and Zeldovich 1972, Doroshkevich et al. 1978). The gas heats up to more than a million degrees, and emits radiation over a broad spectrum, cooling the gas, especially in the central layers, where the density is higher. Recently, Bond, Centrella, Szalay and Wilson (1982) calculated the cooling of collapsing neutrino-baryon pancakes, the details of which are considerably different from those in a pure baryon pancake: the baryon density is lower, but the infall velocities are higher, and thus the cooling rate is much slower. We found that the fraction of cooled baryons is a very sensitive function of the total mass of the collapsing object. Above $\sim 10^{15}$ $M_{\odot}$, no more than about ten percent of the baryons can cool before significant transverse flows take place. This cooling is required, since only cool gas is able to form smaller lumps, the seeds of galaxies. The details of this cooling may be important: a transverse flow in the pancake towards the line singularities will increase the local density, thus enhance cooling. Strings may well be the locations of the most efficient galaxy formation. The UV and soft X-ray emission can photoionize the intergalactic medium, making galaxy formation in regions that have not yet formed pancakes more difficult, which would accentuate the contrast in galaxy density between the strings and pancakes vs. voids, even though the density contrast may be only ~3-10 (Zeldovich and Shandarin 1982). One of the principal difficulties in this picture is how to drive fragmentation at all, since isolated pancakes have no power on small transverse scales. This question was adressed by Doroshkevich (1980), but has not yet been satisfactorily answered.

Cosmic neutrino pancakes may lead to an attractive explanation of the dark halos of galaxies. In the pancake collapse most of the neutrinos acquire large velocities. Some, however, move only slowly at first, since these neutrinos were initially closer to the midplane of the pancake. Around this midplane, we assume a thin gas layer condenses and fragments. Bond, Szalay and White (1982) have constructed a simple one-dimensional model which demonstrates that the slowest moving neutrinos will add on to the baryonic seeds first, followed by progressively faster ones, resulting in a halo which has the total-to-baryonic mass ratio and velocity dispersions needed to describe the halos of spirals. Further, the one-at-a-time addition makes it more likely an r^{-2} halo will form than the r^{-3} found in violent relaxation studies, which would be expected if the dark matter and the baryons collapsed together. Finally, the fraction of neutrinos captured and their velocity dispersion are found to rise with the baryonic mass. The more difficult problem of neutrino capture on galaxies formed along strings has not yet been addressed.

In conclusion, we hope it has become clear that the neutrino-dominated universe seems capable of explaining most features of the large scale structure. At several points in the development of the theory (CBR fluctuations, gas cooling, the phase space constraints of Tremaine and Gunn (1979), the formation of galaxy halos) it just works, which may be the best argument of all for taking it seriously.

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