COSMIC SHOCK WAVES ON LARGE SCALES OF THE UNIVERSE

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In the standard theory of the large scale structure formation, matter accretes onto high density perturbations via gravitational instability. Collisionless dark matter forms caustics around such structures, while collisional baryonic matter forms accretion shocks which then halt and heat the infalling gas. Here, we discuss the characteristics, roles, and observational consequences of these accretion shocks.

The simulations of large scale structure in the universe, which include the evolution of baryonic matter as well as that of dark matter, have shown the formation of accretion shocks around the nonlinear structures such as super-galactic sheets, filaments, and clusters of galaxies (see, for example, Kang et al. 1994). The upper panel of Figure shows the density contours of baryonic matter in one of those simulations (Kulsrud et al. 1997; Ryu, Kang, & Biermann 1997). Accretion shocks exist around the high density structures of clusters, filaments, and sheets in the density contours.

The properties of the shocks and the accreting matter outside the shocks depend upon the power spectrum of the initial perturbations on a given scale as well as the background expansion in a given cosmological model. To study them, we calculated the accretion of dark matter particles around clusters in one-dimensional spherical geometry under various cosmological models (Ryu & Kang 1997). The velocity of the accreting matter around clusters of a given temperature is smaller in a universe with smaller \( \Omega_0 \), but only by up to \( \sim 24\% \) in the models with \( 0.1 \leq \Omega_0 \leq 1 \). It is given as \( v_{\text{acc}} \approx 0.9 - 1.1 \times 10^3 \text{km s}^{-1} \left[ \left( M_d/R_d \right) / \left( 4 \times 10^{14} \text{M}_\odot / \text{Mpc} \right) \right]^{1/2} \). However, the accretion velocity around clusters of a given mass or a given radius depends more sensitively on the cosmological models.

Considering that these accretion shocks are very big with a typical size \( \gtrsim \) a few Mpc and very strong with a typical velocity jump \( \gtrsim \) a few 1000 km s\(^{-1}\), they could serve as possible sites for the acceleration of high energy cosmic rays by the first-order Fermi process (Kang, Ryu, & Jones 1996; Kang, Rachen, & Biermann 1997). With Jokipii diffusion, the observed cosmic ray spectrum near \( 10^{19} \text{eV} \) could be explained with reasonable parameters if about \( 10^{-4} \) of
the infalling kinetic energy can be injected into the intergalactic space as the high energy particles.

The shocks could serve also as sites for the generation of weak seeds of cosmic magnetic field by the Biermann battery mechanism. Then, these seeds could be amplified to strong (up to a few $\mu$G) and coherent (up to the galaxy scale) magnetic field by the Kolmogoroff turbulence endemic to gravitational structure formation (Kulsrud et al. 1997). The lower panel of Figure shows the vectors of seed magnetic field generated by the Biermann mechanism in the simulation. In the highest density regions of clusters, the magnetic field is chaotic since the flow motion is turbulent. However, in the regions which are identified as filaments or sheets, the magnetic field is aligned with the structures due to the streaming flow motion along the structures.

If there is aligned magnetic field in filaments and sheets, this would induce the Faraday rotation in polarized radio waves from extra-galactic sources. Then, an upper limit in its strength can be placed by comparing the expected rotational measure with the observed limit of rotational measure $\text{RM} = 5 \text{ rad m}^{-2}$ at $z = 2.5$ (Kronberg 1994) due to the intergalactic magnetic field. We performed this calculation using the data of the simulation in Figure. The result indicates that, with the present value of the observed limit in rotational measure, the existence of magnetic field of $\lesssim 1\mu$G in filaments and sheets can not be ruled out (Ryu, Kang, & Biermann 1997). It is interesting to notice that the equipartition magnetic field strength in filaments and sheets, $B = 0.77 h \sqrt{T_7 \rho_b / \rho_c} \mu$G, is close to this limit. Here, $T_7$ is the temperature in unit of $10^7$K and $\rho_b / \rho_c$ is the baryonic density in unit of critical density.

One interesting implication of such strong magnetic field in filaments and sheets is its effects on the propagation of high energy cosmic rays through the universe. The discoveries of several reliable events of high energy cosmic rays at an energy above $10^{20}$eV raise questions about their origin and path in the universe, since their interaction with the cosmic microwave background radiation limits the distances to their sources to less than 100 Mpc, perhaps within our Local Supercluster. In Biermann, Kang & Ryu (1996), we noted that if the magnetic field of $\sim 1\mu$G or less exists inside our Local Supercluster and there exist accretion flows infalling toward the supergalactic plane, it is possible that the high energy cosmic rays above the so-called GZK cutoff ($E > 5 \times 10^{19}$eV) can be focused in the direction perpendicular to the supergalactic plane, analogously but in the opposite direction to solar wind modulation. This would explain naturally the correlation between the arrival direction of the high energy cosmic rays and the supergalactic plane. Also, focusing means that for all the particles captured into the sheets, the dilution with distance $d$ is $1/d$ instead of $1/d^2$, increasing the cosmic ray flux from any source appreciably.
Figure 1: Two-dimensional cut of the simulated universe. The plot shows a region of $32h^{-1} \times 20h^{-1}\text{Mpc}^2$ with a thickness of $0.25h^{-1}\text{Mpc}$, although the simulation was done in a box of $(32h^{-1}\text{Mpc})^3$ volume. The upper panel shows baryonic density contours, and the lower panel shows magnetic field vectors.

with respect to the three-dimensional dilution.

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