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The Color Glass Condensate: An Intuitive Description

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Abstract

I argue that the physics of the scattering of very high energy strongly interacting particles is controlled by a new, universal form of matter, the Color Glass Condensate. I motivate the existence of this matter and describe some of its properties.

1 What is the Color Glass Condensate?

The original ideas for the Color Glass Condensate were motivated by the result for the HERA data on the gluon distribution function shown in Fig. 1(a) [1] The gluon density is rising rapidly as a function of decreasing x. This was expected in a variety of theoretical works,[2]-[4] and has the implication that the real physical transverse density of gluons must increase.[2]-[3],[5]. This follows because total cross sections rise slowly at high energies but the number of gluons is rising rapidly. This is shown in Fig. 1(b). This led to the conjecture that the density of gluons should become limited, that is, there is gluon saturation. [2]-[3], [5]

The low x gluons therefore are closely packed together. The strong interaction strength must become weak, $\alpha_S \ll 1$. Weakly coupled systems should be possible to understand from first principles in QCD.[5]-[6]

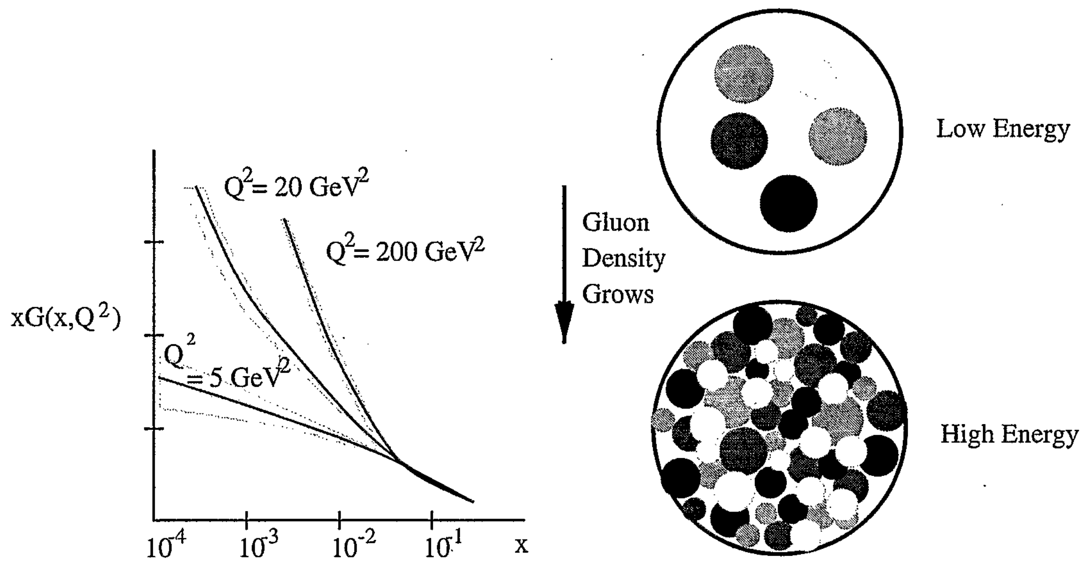

Figure 1: (a)The HERA data for the gluon distribution function as a function of x for various values of Q^2. (b) A physical picture of the low x gluon density inside a hadron as a function of energy.

This weakly coupled system is called a Color Glass Condensate for reasons we now enumerate:[6]

- **Color** The gluons which make up this matter are colored.
- **Glass** The gluons at small x are generated from gluons at larger values of x. In the infinite momentum frame, these larger momentum gluons travel very fast and their natural time scales are Lorentz time dilated. This time dilated scale is transferred to the low x degrees of freedom which therefore evolve very slowly compared to natural time scales. This is the property of a glass.
- **Condensate** The phase space density

$$\rho = \frac{1}{\pi R^2} \frac{dN}{dy d^2 p_T} \qquad (1)$$

is generated by a trade off between a negative mass-squared term linear in the density which generates the instability, $-\rho$ and an interaction term $\alpha_S \rho^2$ which stabilizes the system at a phase space density $\rho \sim 1/\alpha_S$. Because $\alpha_S << 1$, this means that the quantum mechanical states of the system associated with the condensate are multiply occupied. They are highly coherent, and share some properties of Bose condensates. The gluon occupation factor is very high, of order $1/\alpha_S$, but it is only slowly (logarithmically) increasing when further increasing the energy, or decreasing the transverse momentum. This provides saturation and cures the infrared problem of the traditional BFKL approach.[7]

Implicit in this definition is a concept of fast gluons which act as sources for the colored fields at small x. These degrees of freedom are treated differently than the fast gluons which are taken to be sources. The slow ones are fields. There is an arbitrary X_0 which separates these degrees of freedom. This arbitrariness is cured by a renormalization group equation which requires that physics be independent of X_0. In fact this equation determines much of the structure of the resulting theory as its solution flows to a universal fixed point.[6]-[9]

There is evidence which supports this picture. One piece is the observation of limiting fragmentation. This phenomena is that if particles collide at some fixed center of mass energy and the distribution of particles are measured as a function of their longitudinal momentum from the longitudinal momentum of one of the colliding particles, then these distributions do not change as one goes to higher energy, except for the new degrees of freedom that appear. This is true near zero longitudinal momentum in the center of mass frame because new degrees of freedom appear as the center of mass energy is increased. In the analogy with the CGC, the degrees of freedom, save the new ones added in at low longitudinal momentum, are the sources. The fields correspond to the new degrees of freedom. The sources are fixed in accord with limiting fragmentation. One generates an effective theory for the low longitudinal momentum degrees of freedom as fixed sources above some cutoff, and the fields generated by these sources below the cutoff. A recent measurement of limiting fragmentation comes from the Phobos experiment at RHIC shown in Fig. 2 [10]

Of course the perfect scaling of the limiting fragmentation curves is only an approximation. As shown by Jalilian-Marian, the limiting fragmentation curves are given by the total quark, antiquark and gluon distribution functions of the fast particle measured at a momentum

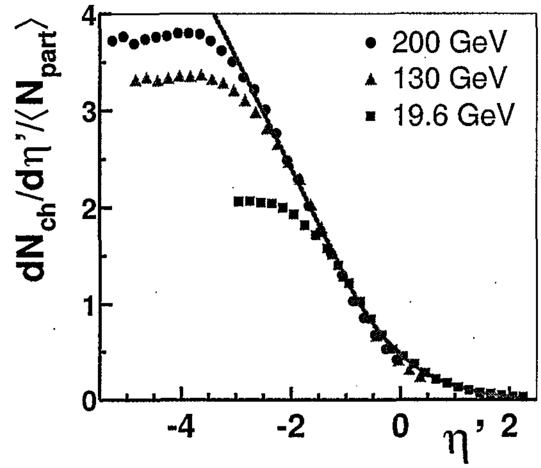

Figure 2: Limiting fragmentation and the RHIC data.

scale Q^2_{sat} appropriate for the particle that it collides with.[11] The saturation momentum Q_{sat} will play a crucial role in our later discussion. It is a momentum scale which is determined by the density of gluons in the CGC

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_S} Q^2_{sat} \tag{2}$$

The saturation momenta turns out to depend on the total beam energy because the longitudinal momentum scale of the target particle at fixed x of the projectile will depend upon the beam energy. It is nevertheless remarkable how small these violations appear to be.

The CGC may be defined mathematically by a path integral:

$$Z = \int_{X_0} [dA][dj] exp \left(iS[A, j] - \chi[j] \right) \tag{3}$$

What this means is that there is an effective theory defined below some cutoff in x at X_0, and that this effective theory is a gluon field in the presence of an external source j. This source arises from the quarks and gluons with $x \geq X_0$, and is a variable of integration. The fluctuations in j are controlled by the weight function $\chi[j]$. It is

$\chi[j]$ which satisfies renormalization group equations which make the theory independent of X_0.[8]-[14],[6]. The equation for χ is called the JIMWLK equation. This equation reduces in appropriate limits to the BFKL and DGLAP evolution equations.[4], [15] The theory above is mathematically very similar to that of spin glasses.

There are a variety of kinematic regions where one can find solutions of the renormalization group equations which have different properties. There is a region where the gluon density is very high, and the physics is controlled by the CGC. This is when typical momenta are less than a saturation momenta which depends on x,

$$Q^2 \leq Q^2_{sat}(x) \tag{4}$$

The dependence of x has been evaluated by several authors, [2],[16]-[18], and in the energy range appropriate for current experiments has been determined by Triantafyllopoulos to be

$$Q^2_{sat} \sim (x_0/x)^\lambda \; GeV^2 \tag{5}$$

where $\lambda \sim 0.3$. The value of x_0 is not determined from the renormalization group equations and must be found from experiment.

There is also a region of very high Q^2 at fixed x, where the density of gluons is small and perturbative QCD is reliable. It turns out there is a third region intermediate between high density and low where there are universal solutions to the renormalization group equations and scaling in terms of Q^2_{sat}.[17] In this region and in the region of the CGC, distribution functions are universal functions of only $Q^2/Q^2_{sat}(x)$. The extended scaling region is when

$$Q^2_{sat} \leq Q^2 \leq Q^4_{sat}/\Lambda^2_{QCD} \tag{6}$$

2 What is the CGC Good For?

The CGC provides a unified description of deep inelastic structure functions, of deep inelastic diffraction and of hadron-hadron collisions at high energies. It is the high energy limit of QCD. As such, it has many test to pass before being accepted as a correct description. Over the last several years, there have been many qualitative and semi-quantitative successes of this description. It also provides an intuitively plausible and mathematically consistent description of such phenomena.

In the future years, there will be increasingly stringent tests arising at RHIC, LHC and potentially eRHIC. Theoretically, we are just beginning to understand the properties of this matter. New ideas concerning the structure of the underlying theory and the breadth of phenomena it describes are changing the way we think about high energy density matter.

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