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The Formation of the Universe from Rotating Superstrings

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Abstract

The examination of the masses and angular momenta of a wide variety of astronomical objects, ranging from planets to clusters of galaxies, suggests that astronomical objects were originally formed from rotating superstring. Each piece of rotating string breaks into smaller pieces with masses corresponding to smaller astronomical objects. One possibility is that the Universe starts as one piece of rotating superstring.

1. Introduction

The formation of structure in the Universe remains a problem of concern in cosmology (Peebles 1984; Frankel and Spark 1986), and it is expected that the theories of high energy physics are relevant to this problem. It will be shown that the consideration of the angular momenta of astronomical objects leads to a picture in which all the matter of the Universe comes from a cascade of fragmentation of rotating superstrings.

Discussing the theories of the formation of structure in the Universe, Peebles (1984) pointed out that there are 'top–down' scenarios in which the observed structures form from the break-up of larger structures, such as the pancake theory (Zeldovich *et al.* 1982), 'bottom–up' scenarios such as the proposal by Lemaître (1934) that the observed structures form as a result of gravitational instability in a homogeneous Universe, and hybrids of these two types of scenario. The scenario of a Universe evolving from the fragmentation of one initial rotating superstring is an extreme form of a 'top–down' scenario.

It is the purpose of this paper to discuss further and in more detail some of the considerations reported earlier (Tassie 1986). In particular Section 5 is a modified and more detailed treatment of string fragmentation.

2. Astronomical Angular Momenta

Brosche (1963, 1969, 1980, 1986) pointed out that

$$J = \kappa M^2 \tag{1}$$

for a wide variety of astronomical objects, ranging from planets to the local supercluster of galaxies, where J and M are the angular momentum and the mass respectively

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of the object, and κ is a universal constant. A more recent analysis by Wesson (1979, 1981) gave the value $\kappa = 8\times10^{-16}\ \mathrm{g}^{-1}\,\mathrm{cm}^2\,\mathrm{s}^{-1} = 4\times10^2\ G/c$ where G is the Newtonian gravitational constant and c is the velocity of light. There is considerable uncertainty in the value of κ as Wesson obtained $\log_{10}\kappa = -15\cdot1\pm0\cdot9$.

There is a large variation of angular momentum for each class of astronomical objects. Brosche (1980) pointed out that the J–M diagrams of all classes exhibit a real two-dimensional manifold, and that for each class alone, the J–M diagrams permit a range of J–M relationships for the different classes with a variation in the exponent β of a power law

$$J \propto M^{\beta},$$

but that all classes together are described by equation (1) holding for over 20 powers of 10 in the mass. It is very difficult to decide how much of the dispersion in each class is real or due to uncertainties in the determinations of J and M. An analysis by Carrasco *et al.* (1982) claimed that within each class of objects $\frac{5}{3} \leqslant \beta \leqslant \frac{7}{4}$ and that the relationship between J and M is scaled by a weak power of the density to produce the fit of equation (1) when all classes of objects are considered. The β is determined from the slope of a linear regression of $\log J$ against $\log M$, but for objects of one class the determination of β is not very reliable because the values of $\log J$ and $\log M$ are all very close together and also because the errors in the determinations of M and J are not always independent, as has been stressed for the case of spiral galaxies by Freeman (1970) and Nordsieck (1973).

When all classes of objects are considered, Carrasco *et al.* (1982) found $\beta = 1\cdot94\pm0\cdot09$ which, as pointed out by Wesson (1983), provides strong confirmation of equation (1).

Wesson (1981, 1984) has given a dimensional argument for the relation (1) but did not provide any physical model of how this occurs. Wesson also pointed out that the value of κ is consistent with $\kappa = G/c\alpha$ where α is the dimensionless electromagnetic fine-structure constant, $\alpha = e^2/4\pi\hbar c \approx \frac{1}{137}$.

3. Strings

Brosche (1969, 1980) pointed out the similarity of equation (1) to the relation for the Regge trajectories of hadrons, for which (Barger and Cline 1969)

$$J(M) = \kappa_{\mathrm{h}}\, M^2 + J(0)\,, \tag{2}$$

where $\kappa_{\mathrm{h}} = \hbar/(\mathrm{GeV}/c^2)^2 = 1\cdot5\times10^{38}\ G/c$.

Since κ_{h} differs so greatly from κ for astronomical objects, it is clear that the spectrum of astronomical objects is not directly related to the spectrum of hadrons. However, there is a simple physical model of the hadrons in which the spectrum (2) is the spectrum of the rotational states of a string (Rebbi 1974; Olesen 1975; Marinov 1977). The string parameter is μ, the mass per unit length, also called the string tension. For a rigidly rotating straight open string, we have

$$\kappa = c(2\pi\mu)^{-1}\,. \tag{3}$$

For rigidly rotating closed strings, the right-hand side of equation (3) contains an additional factor ranging from $\frac{1}{2}$ to $\frac{1}{6}$ according to the particular class of solutions

(Burden and Tassie 1982*a*, 1982*b*, 1984), and such a factor can be neglected in view of the uncertainty in κ for astronomical objects.

Assuming that equation (1) for astronomical objects also represents the spectrum of a rotating string, the astronomical string has $\mu_a = 6\times10^{24}\ \mathrm{g\,cm^{-1}} = 4\times10^{-4}\ c^2/G$. This value of the string tension can be compared with the string tensions summarised (Tassie 1986) in Table 1 for the various types of strings that have been considered in particle physics.

Table 1. String tensions for various types of strings considered in particle physics

String	String tension μ	String	String tension μ
Astronomical	$4\times10^{-4}\ c^2/G$	SO(10) (Kibble *et al.* 1982)	10^{-3}–$10^{-5}\ c^2/G$
Hadronic	$10^{-39}\ c^2/G$	Non-hadronic	
Electroweak	$2\times10^{-33}\ c^2/G$	(Scherk and Schwarz 1974)	$5\times10^{-5}\ c^2/G$
GUT	$2\times10^{-7}\ c^2/G$	Heterotic superstring	$3\times10^{-3}\ g^2\,c^2/G$
SUSY GUT	$10^{-4}\ c^2/G$		

The theory of the superstring (Green 1985) is claimed to be a theory of all interactions. For type I string theories (Schwarz 1982; Green and Schwarz 1984), which describe the dynamics of open strings, the string tension is given by (using units with $\hbar = c = 1$)

$$\mu = \text{const.}\ G^{\frac{1}{2}}/g^2 \tag{4}$$

in ten-dimensional spacetime, where g is the elementary non-abelian charge. The gauge field coupling constant, analogous to the fine structure constant $\alpha \approx \frac{1}{137}$ for quantum electrodynamics, is $\alpha_G = g^2/4\pi$. Assuming that six dimensions are compactified (Schwarz 1982; Green *et al.* 1985) by imposing periodic boundary conditions with period $2\pi R$, we have

$$\mu_I = \text{const.}\,(G^{\frac{1}{2}}/g^2)R^{-3}\,, \tag{5}$$

and comparison with the astronomical value of μ is not possible without an estimate of the compactification radius R.

For the heterotic string (Gross *et al.* 1985*a*, 1985*b*) the string tension is given by (Gross *et al.* 1986)

$$\mu_{II} = g^2/32\pi^2 G \tag{6}$$

and, if it is again assumed that the compactification from ten- to four-dimensional spacetime is given by imposing periodic boundary conditions with period $2\pi R$, this relation is not affected by the compactification. Other ways of obtaining the compactification from ten to four dimensions can introduce a geometrical factor depending on the details of the compactification. Using equation (6), agreement with the astronomical value for μ is obtained if $g^2 \approx 0{\cdot}1$. Until the phenomenology of the low energy approximation to the heterotic string is well established, it cannot be decided if this value of g^2 is reasonable.

Table 1 shows that an interpretation of the observed J–M relation of astronomical objects in terms of a string model seemed definitely far-fetched when the strings available in particle theory were the hadronic string, the electroweak string, or even the GUT (grand unified theory) string. However, the convergence of the string tension of the particle physics models, and in particular of the string tension obtained for the superstring, towards the string tension determined from the astronomical observations encourages the interpretation of (1) in terms of strings.

4. Evolution of the Universe

Kibble (1976, 1985) and others (Zeldovich 1980; Vilenkin 1981; Kibble *et al.* 1982; Kibble and Turok 1982; Turok 1983, 1984; Albrecht and Turok 1985) have suggested that GUT strings play an important part in the evolution of the Universe and that strings provide the inhomogeneity leading to the formation of galaxies. In these theories the strings constitute only a small fraction of the mass of the Universe; galaxies are formed by the accretion of ordinary matter about the strings, and some strings may still be present, even possibly nearby.

However, the explanation of (1) in terms of strings suggests a very different evolution of the Universe, namely that at some past time strings constituted all or nearly all of the mass of the Universe, and that astronomical objects were originally formed from string in such a way that a large piece of string, which eventually corresponds to a supercluster of galaxies, breaks into smaller pieces, which eventually correspond to clusters of galaxies. These pieces of string in turn break into smaller pieces corresponding to galaxies, and so on for all astronomical objects obeying equation (1). At each stage in this hierarchy of breaking of strings, the new pieces of string may have some vibrational energy, but the vibrational energy would have to be large compared with the mass to cause an appreciable deviation from equation (1), and also it is expected that the transfer of such vibrational energy into kinetic energy of the neighbouring strings can occur more readily than the transfer of angular momentum, so that it is expected that each piece of string would soon be in a state with the minimum energy for a given angular momentum. A similar situation occurs in nuclear physics where an excited nucleus eventuating from a heavy ion collision will soon settle into a 'yrast' state (Grover 1967; Bohr and Mottelson 1975), a state of maximum spin for a given energy. In particle physics, a 'yrast' state corresponds to a state on the leading Regge trajectory.

Eventually at some later stage the pieces of string transform, possibly by a phase transition, into ordinary matter and become the stars and planets that we now observe. An alternative possibility to a phase transition is that the pieces of string continue to break up eventually resulting in very small pieces of string, corresponding to $J \sim \hbar$, which combine to form the ordinary particles of physics that now make up the Universe. At some stage in the hierarchical fragmentation of strings, other forces become more important than the gravitational interaction so that all traces of the relationship (1) are lost for sufficiently small objects. The larger composite objects, planets, stars and galaxies will have much the same relation between mass and angular momentum as the pieces of string from which they evolve, as they will not lose a large proportion of their angular momentum or mass. They may radiate a large amount of energy, but this will in general have a small effect on the order of magnitude of their mass. So the spectrum of the string would be preserved in the currently observed astronomical objects, providing an explanation of the agreement of the astronomical value of κ with that of strings of the theory of high energy physics.

5. String Fragmentation

A thermodynamic description of string fragmentation can be obtained by modifying the treatment of Aharonov and Casher (1986) to include the effect of angular momentum. They have proposed that the initial state of the Universe is a single string. Using a thermodynamic argument, they concluded that a cascade process in which the string breaks into lighter strings of finite mass requires a decrease in entropy and so will not occur. They concluded that the initial string decays into massless particles. However, Aharonov and Casher did not consider the break-up of a string with large angular momentum. The density of states of the string falls off exponentially with increasing angular momentum, and a modification of the treatment of Aharonov and Casher to include the effect of conservation of angular momentum leads to the very different conclusion that the string does fragment into lighter strings of finite mass.

The treatment here is of an open string (instead of the closed string considered by Aharonov and Casher) with large angular momentum breaking into N open strings, with N sufficiently large for the effect of conservation of total angular momentum on the entropy of the system of N strings to be negligible. The density of states for each of the N strings is (Aharonov and Casher 1986)

$$\rho(m) \sim k m^{-a} \exp(m/T_c), \tag{7}$$

where m is the mass of the string, and T_c is the Hagedorn temperature of the string. For the open bosonic string in D transverse dimensions we have $T_c = (3\mu/\pi D)^{\frac{1}{2}}$. The entropy of a system, composed of a large number N of strings whose average mass is m and whose average of the absolute value of momentum is p, is given by Aharonov and Casher (1986) as

$$S(N, m, p) \sim N\{\ln(p^d v) + m T_c^{-1} - a \ln m\}, \tag{8}$$

where v is the average volume occupied by the centre-of-mass of a string and d is the number of space dimensions.

The density of states of the initial string of mass M with angular momentum J is given by (Chiu *et al.* 1971; Chiu and Heimann 1971; Nahm 1977)

$$\bar{\rho}(M, J) \sim \bar{k} M^{(-a-2)} \exp\{M T_c^{-1} - \pi\mu J (M T_c)^{-1}\} \quad \text{for} \quad J < M^2/2\pi\mu \tag{9a}$$

$$= 0 \quad \text{for} \quad J > M^2/2\pi\mu . \tag{9b}$$

For convenience, the approximation $J \gg (\frac{3}{2})^{\frac{1}{2}}\pi(M^2/2\pi\mu)^{\frac{1}{2}}$ has been used to simplify equation (9a). The entropy for the initial string is

$$S(M, J) \sim M T_c^{-1} - \pi\mu J (M T_c)^{-1} - (a+2) \ln M . \tag{10}$$

Then following Aharonov and Casher (1986), neglecting $\ln M$ and $\ln m$, and noting that $M - Nm$ is just the total kinetic energy of the system of N strings which we write as

$$(M - Nm) = N T_p ,$$

where T_p is the average kinetic energy of the resulting strings, we have

$$S(M, J) - S(N, m, p) \sim N\{ T_p T_c^{-1} - \ln(p^d v)\} - \pi\mu J(M T_c)^{-1}. \quad (11)$$

For small J the conclusions of Aharonov and Casher apply and the string does not break into smaller pieces. For large J and large T_p, if

$$\pi\mu J M^{-1} > (M - N m) \quad (12)$$

the entropy increases when the string breaks into N pieces. It is convenient to write

$$M = (2\pi\mu J)^{\frac{1}{2}} + v. \quad (13)$$

For the straight rotating string we have $v = 0$, and for large J, $v \ll M$. The condition (12) can be written as

$$N m > \tfrac{1}{2} M + v(1 - \tfrac{1}{2} v/M), \quad (14)$$

i.e. over half the original total energy is preserved as rest mass. The original string cannot decay into massless particles.

6. Discussion

While the description of the Universe in terms of the fragmentation of strings leads to the relationship between J and M observed over many classes of astronomical objects, it is expected that within each class there will be later evolutionary effects such as some changes in J by tidal interactions (Peebles 1969, 1980) and possibly changes of J and M by collisions. For instance it seems that Mercury with $J/M^2 = 0{\cdot}014 \times 10^{-15}$ $g^{-1}\,cm^2\,s^{-1}$ and Venus with $J/M^2 = 0{\cdot}008 \times 10^{-15}$ $g^{-1}\,cm^2\,s^{-1}$ have lost angular momentum by later effects.

It should be noted that there are theories of the angular momenta of a particular class of astronomical objects such as the primeval turbulence theory (Ozernoi 1978) and the tidal torque theory (Peebles 1969, 1980; Fall and Efstathiou 1980; Fall 1983) of the angular momenta of galaxies, but there is no other model to give a single explanation of the angular momenta of many classes of astronomical objects as does the string model.

In the picture proposed by Kibble (1976, 1985) and others (Zeldovich 1980; Vilenkin 1981; Kibble *et al.* 1982; Kibble and Turok 1982; Turok 1983, 1984; Albrecht and Turok 1985) GUT strings act as the starting point of galaxy formation but the string is a small part of the mass of the galaxy. Most of the mass of the galaxy comes from ordinary matter which is originally distributed uniformly through the Universe and which condenses about each piece of string to form a galaxy. If galaxy formation occurred in this way, then the Universe must have been more homogeneous in the past than the present Universe, and looking at large distances we should see a more homogeneous Universe than we see in the nearby part of the Universe.

On the other hand, if the Universe evolves from the break-up of rotating string, the galaxies and clusters of galaxies that eventually form from the fragmentation of string would be originally arranged in a manner indicative of a string. They would be strung out like beads on an invisible string. The more time that has elapsed, the less indication should remain of the original string structure. In the distant parts of the Universe, we should see galaxies etc. that have not had very much time to move from their original positions as pieces of string. The more distant objects of the Universe should appear to us to trace out the configurations of the strings more closely than the nearby objects. Looking at large distances we should see a more inhomogeneous Universe than we see in the nearby part of the Universe.

There are various possibilities for the original configuration of a string Universe. One extreme possibility is that the Universe started with a random distribution of string sizes. In this case, since the size determines the type of object that the string evolves into, there should be some galaxies not in clusters, some star clusters not in galaxies and so on, possibly including even isolated planets. The simplest assumption is that the Universe was originally one piece of superstring as suggested by Aharonov and Casher (1986), but if the string picture of the structure of the Universe is correct, that original string was rotating. Then one would expect the Universe to obey equation (1) with the universal value of κ. The values of J and M given for the Universe by Sisteró (1983) are in contradiction with this expectation. However, neither J nor M for the Universe are known yet with sufficient accuracy for this contradiction to be taken too seriously at this stage.

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