Personnal recollections about the birth of String Theory*

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In 1969, I was finishing my Ph.D. in Orsay under the supervision of Michel Gourdin on phenomenological works related to e^+e^- annhilations. These works allowed me to deepen my knowledge in particle physics as well as to learn mastering difficult calculations. However, I was more attracted by more formal research (that we would like being able to say more fundamental!). The theoretical physics laboratory in Orsay was also hit by the explosion of activity which followed the paper of Veneziano, and a group of people began to work on dual models: Bouchiat, Gervais, Nuyts, Amati who was spending a sabbatical in Orsay, as well as younger researcher Neveu, Scherk and Sourlas. My first encounter with dual models was to rebel against this too fashionable growing activity. With Jean Nuyts I asked if there could be some other example of a s-t dual amplitude with only poles in both channels: we found an example with poles lying on a logarithmic trajectory instead of a linear one [1]. However this amplitude led to many unsatisfactory physical conclusions and I joined the main stream.

1 Factorizing the Pomeron with Joël Scherk at CERN

In 1970, much work was devoted to the dual multiloop amplitude, in particular by Kaku and Yu [2]. Lovelace [3] and Alessandrini [4] showed the relation between these amplitudes and the Neumann function associated with a sphere with handles. I then began a rather technical work, the study of a multiloop operator and its dual properties [5]. I had the chance to get a fellow position at the theory division at CERN for 2 years (1971 and 1972). This was the first chance of my career. The second one was to "integrate" the dual group at CERN which was led by Daniele Amati. In this group, there was not only a very stimulating scientific atmosphere, but also a very friendly one. At that time the theory division had more than a hundred people and the fellows who were not associated with a group could easily stay isolated. Then arrived my third and most important chance, the venue of Joël Scherk and the beginning of our collaboration. I knew of course Joël from Orsay and had had discussions with him although not belonging to the same "team" (Bouchiat-Meyer for Joël, Gourdin for me), but I had had no opportunity to work with him. As early as that stage, Joël was a profound physicist. He was a very quiet and efficient physicist. His notes were very clear and are still readable many years later (contrary to mine!), the detailed calculations were always accompanied by some commentary.

After some works on multicurrents dual amplitude [6, 7], where we had some mathematical fun with domain variational theory on Riemann surfaces, we came back to a less technically demanding problem but more irritating one. The one-loop diagrams (and multiloop) are constructed from unitarity and should have analytic properties resulting from unitarity (namely unitarity cuts and eventually poles). However in the non-planar orientable, it appears in the channel with zero isospin (associated with the "pomeron") a new singularity violating unitarity. Lovelace [8] showed that when the intercept is 1 this singularity is factorisable, furthermore he conjectured that in 26 dimensions 2 sets of oscillators are cancelled by gauge conditions leading to a modification of the amplitude which has no longer cut but poles so that unitarity is no longer violated. This conjecture will be shown later. When the intercept is one (implying the existence of a massless vector particle) and the dimension is less or equal to 26 (for pure bosonic model), the dual resonance model is ghost free (the time dimension is eliminated by the gauge invariance associated with the intercept 1). In 26 dimensions, null states appear that should also be eliminated. The complete formula for the loop amplitude was to be proven later after the projector on the physical states had been constructed. Starting with the conjectured form of the amplitude [9] we factorized the reggeon and the pomeron poles simultaneously. The pomeron sector looks quite similar to the Shapiro-Virasoro model with a slope half that of the reggeon trajectory and an intercept equal to 2 (implying a massless spin 2 particle). In the string language, this will correspond to the transition from an open string to a closed string. From the 2-non planar loops diagram with 3 external reggeons, it is possible to extract a 3-pomeron vertex. The appearance of this sector of new particles shows that the Veneziano model (open strings) is not consistent alone and that we must also include the Shapiro-Virasoro model (closed strings) This has been done independently by Clavelli and Shapiro [10] who have extended it to the Neveu-Schwarz-Ramond model in 10 dimensions.

2 Combining and splitting Strings with Jean-Loup Gervais in Orsay

Back in Orsay in 1973, I began a collaboration with Jean-Loup Gervais. The introduction of the string picture had improved tremendously our physical understanding of dual models. Associated with the string picture is the functional approach to dual theories. The initial works of Hsue, Sakita and

Virasoro [11] and those of Gervais and Sakita [12, 13] were plagued by their inability to project out the ghost states but explicitly exhibited two important properties of dual models which are not so transparent in the operator formalism, namely duality and the connection between loop amplitudes and Neumann functions. As far as the Veneziano model is concerned, a crucial progress was made by Goddard et al. [14] who showed that the Lagrangian of the free relativistic string being gauge-invariant, one needs only to quantize the transverse components of the string variable if one chooses the appropriate gauge. Gervais and Sakita [15] subsequently wrote the path integral associated with transition probabilities of strings with this gauge condition, in such a way that one can perform the functional integration and obtain the original Veneziano amplitude. Later Mandelstam [16], starting from this amplitude, gave a complete prescription for dealing with external excited states as described by Goddard et al.. He proved that the resulting amplitude is Lorentz-invariant only at 26 space-time dimensions and that the three-reggeon vertex coincides with the one given by Ademollo et al (ADDF) [17], thus establishing complete connection between the string formalism and the operator formalism of the Veneziano model. Kaku and Kikkawa [18] have introduced a multi-string formalism in a consistent way such that the topological structure of the corresponding perturbation series is identical with the structure of the dual theory, each dual amplitude being obtained as a sum of several Feynman graph contributions. This formalism, based on a functional treatment of the string variable, remained ambiguous because of the lack of precise definition of the functional integration while a careful determination of the functional integration measure is necessary to obtain Lorentz-invariant amplitudes that coincide with dual amplitudes. Gervais and I overcome this problem by developing an infinite component field theory of interacting relativistic strings starting from operator approach. In particular we introduced a 3-string vertex either for 2 incoming strings $\rightarrow$ 1 outgoing string (combining strings) or for 1 incoming string $\rightarrow$ 2 outgoing strings (splitting strings). It was simply defined as the overlapping of the 3 strings at a given time. We showed that it was related to the ADDF three-reggeon vertex by allowing each of the 3 strings to propagate for a very long time [19]. We then showed [20] that in order to get the correct 2 incoming strings $\rightarrow$ 2 outgoing strings amplitude, it was necessary to add a direct 4-string interactions to the sum of 2 Feynman diagrams constructed from the 3-string vertex and a propagator. This defined the 4-string vertex introduced by Kaku and Kikkawa. who had shown that three- and four-strings vertices were sufficient in the tree approximation. The formalism to all orders can be defined but it is necessary to also introduce an infinite component field associated to the closed string and in addition to closed strings vertices also define a transition vertex between open and closed strings. Although satisfactory from the point of view of precise definition, this formalism is very hard to use in practice as was already seen in the 4-string amplitude.

3 Compactifying Strings with Joël Scherk at LPTENS

In october 1974, a group of physicists of the theoretical physics laboratory in Orsay (essentially the Bouchiat-Meyer group that I joined on my return from CERN) moved to Paris and founded the "Laboratoire de Physique Théorique de l'Ecole Normale Supérieure".

A very elegant feature of dual models is to predict the dimension of space-time namely 26 for the Veneziano and Shapiro-Virasoro models and 10 for the Neveu-Schwarz-Ramond model. Unfortunately these predictions are rather unphysical, moreover these models are predicting zero mass particles and are therefore incompatible with hadronic physics. It is worth to remember that the same "avatar" happened to Yang-Mills theory. This led Scherk and Schwarz [21] as well as Yoneya [22] to study the connection between dual models and general relativity in particular in the zero slope limit which was known to make connection between dual models and field theory. In 1975, Scherk and Schwarz [23] made the really daring proposal that dual models should be interpreted as a quantum theory of gravity unified with the other forces between quarks and gluons. They suggested that considering some of the dimensions to be compact does not lead to any contradiction within the framework of dual models. Scherk and I proved that this assertion was indeed correct [24]. This was the beginning of a new and very fruitful collaboration with Joël. We defined the theory of open and closed strings on a compact space (chosen to be a hypertorus). In a field theory on a compact space the momenta in the compactified directions (hyper torus of radii R_i) is quantized ($p_i = n_i/R_i$) and with a single field is associated an infinite Kaluza-Klein multitower of fields in lower dimension. For open strings this is also the only change. For closed strings the change is less trivial, although simple. One must introduce another integer number (winding number) m_i corresponding to how many times a string wraps around the torus before closing. The new states corresponding to the quantum numbers n_i and m_i get now an additional mass M_i given by

$$M_i^2 = n_i^2/R_i^2 + m_i^2 R_i^2/\alpha'^2$$

We showed that the corresponding modification to the computation of loops like replacing the integration on the momentum flowing in the loop by a summation on the quantized momenta did not affect all the good results like the absence of non physical singularities in the non planar orientable loop and the appearance of new particles associated to the compactified closed string. I must confess that our field theory prejudice on the limit R infinite and R nul prevented us to discover the T-duality of closed string theory, namely the complete symmetry

$$n_i \to m_i, m_i \to n_i, R_i \to \alpha'/R_i$$

Generalized to the torus associated with a group, this compactification of closed strings was to lead to the construction of the heterotic string [25] in 1985. It is important also to note that this kind of compactification is equivalent to introduction of quantum numbers in string theory by Bardacki and Halpern [26].

At that time, I turned to a new direction of work still with Joël Scherk - until his unfortunate death in 1980 - and others. This became my Supergravity Era but

This is another story

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