International Journal of Modern Physics A

Phenomenological properties of unoriented D-brane models

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Received Day Month Year
Revised Day Month Year

D-brane realizations of the Standard Model predict extra abelian gauge fields which are superficially anomalous. The anomalies are cancelled via appropriate couplings to axions and Chern-Simons-like couplings. The presence of such couplings has dramatic experimental consequences: a) they provide masses to the anomalous abelian gauge fields (which masses can be of order of a few TeV), b) they provide new contributions to couplings like Z'-¿gamma Z, that may be considerable at LHC. This proceeding is mainely based on hep-th/0605225.

Keywords: D-branes; Anomalies; Anomalous U(1); Standard-Model; Z′

PACS numbers: 11.25.Hf, 123.1K

1. Introduction

One of the most interesting and demanding problems is to embed the Standard Model in string theory. Many attempts have been made with partial success, other in the direction of heterotic theories and others in D-brane models[1−15]. We will focus our attention on the later since they provide the nobel possibility that the string scale is much lower than the Planck scale.

In such a context the Standard Model particles are open string states attached on (different) stacks of D-branes. N coincident D-branes typically generate a unitary group U(N). Therefore, every U-factor in the gauge group supplies the model with extra abelian gauge fields.

Such U(1) fields have generically 4d anomalies. The anomalies are cancelled via the Green-Schwarz mechanism [16,17,33] where a scalar axionic field (zero-form, or its dual two-form) is responsible for the anomaly cancellation. This mechanism gives a mass to the anomalous U(1)'s and breaks the associated gauge symmetry. The masses of the anomalous U(1)s are typically of order of the string scale but in open string theory they can be also much lighter [2,18,19,20]. If the string scale is around a few TeV, observation of such anomalous U(1) gauge bosons becomes a realistic possibility [21,22].

Nevertheless, Green-Schwarz mechanism is not enough to cancel all the anomalies. Mixed abelian anomalies between anomalous and non-anomalous factors need generalized Chern-Simons terms to be cancelled. Here, we present our results by using a toy-model.

Next, we describe the bottom-up approach of the Standard Model embeddings in type I string theory and we focus in a representative model which apart from the Standard Model particles, it also contain three anomalous U(1)'s, three axions and three pairs of Higgs doublets [8,10]. If these anomalous U(1)'s have masses in the TeV range, they behave like Z' gauge bosons widely studied in the phenomenological literature [21−25].

As we mention above, the presence of anomalous and non-anomalous U(1)'s (the hypercharge) requires generalized Chern-Simons terms. These anomaly related couplings produce new signals that distinguish such models from other Z' models. If the string scale is of order of a few TeV, such signals may be visible in LHC [24].

This paper is organized as follows: In section 2 we present the general analysis of the anomaly related effective actions and the Green-Schwarz mechanism. We also argue with a toy-model, that cancellation of mixed anomalies of anomalous and non-anomalous U(1)'s require generalized Chern-Simons terms. In section 3 we explore a four stack D-brane model which can describe the Standard Model, and we give some phenomenological aspects of the generalized Chern-Simos terms.

2. Anomalies

Consider for simplicity only one anomalous U(1). In terms of a gauge transformation $A_\mu \to A_\mu + \partial_\mu \epsilon$ of the effective action, the anomalies are:

$$\delta_\epsilon S = \int d^4x \left\{ \epsilon \ (\mathcal{A}_1 \ F \wedge F + \mathcal{A}_2 \ Tr[G_a \wedge G_a] + \mathcal{A}_3 \ R \wedge R) \right\} , \qquad (2.1)$$

where F^A, G^a field strengths of the anomalous A^μ and a non-abelian field G^α_μ. Also $\mathcal{A}_1 = Tr[Q^3]$, $\mathcal{A}_2 = Tr[QT^aT^a]$ and $\mathcal{A}_3 = Tr[Q]$ the group theory factors. We suppress the indexes for simplicity. We also remind that $F \wedge H \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}H_{\rho\sigma}$.

First, we will concentrate our study in the mixed (second) anomalous diagram and we will describe the Green-Schwarz mechanism that cancels the mixed anomaly between abelian and not-abelian factors [16,17,33]:

The fields that contribute to the anomaly cancellation are antisymmetric tensors $B^k_{\mu\nu}$ and they are coming from the kth twisted closed string spectrum (they are RR fields). However, it is more convenient to use the Poincaré dual of $B_{\mu\nu}$ scalar field α (axion):

$$\mathcal{L}_\alpha = -\frac{1}{4g_A^2}F^AF^A - \frac{1}{4g_a^2}Tr[G^aG^a] - \frac{1}{2}\left(\partial^\mu\alpha - MA^\mu\right)^2 - \frac{1}{2}\ c_1\ \alpha\ Tr[G^a \wedge G^a]\ . \qquad (2.2)$$

where $M,\ c_1$ constants. Notice that the third term in the lagrangian is not invariant under a U(1) gauge transformation unless the axion α also transforms like:

$$A^\mu \to A^\mu + \partial^\mu \epsilon \ , \qquad \alpha \to \alpha + M\epsilon \ . \tag{2.3}$$

This transformation of the axion generates a non-invariance coming from the fourth term in (2.2). This term will annihilate the anomalous term that is generated by the fermionic transformation, giving an anomaly free gauge theory. The total variation of the lagrangian under the above gauge transformation is:

$$\delta_\epsilon \mathcal{L}_{total} = -\frac{1}{2}\Big(Mc_1 - \frac{\mathcal{A}_2}{16\pi^2}\Big)\ \epsilon\ Tr[G^a \wedge G^a] \ , \tag{2.4}$$

where the first term is coming from the variation of $\mathcal{L}_\alpha$ and the second are the mixed anomalies from the variation of the measure of the chiral fermions. The anomaly is cancelled for: $\mathcal{A}_2 = 16\pi^2 M c_1$.

The NSNS-twisted moduli m (SUSY partner of α which form together a complex scalar field $\phi = m + i\alpha$) couple to the vector fields generating Fayet-Iliopoulos D-terms:

$$S_{FI} = \int d^4x \frac{1}{g_A^2}\Big(m + \sum_i q_i |\Phi_i|^2\Big)^2 \ . \tag{2.5}$$

where Φ_i denote various open strings with charge q_i under the anomalous U(1)s. On the fixed points we have: $\langle m \rangle = 0$. The global $U(1)_A$ remains unbroken despite the fact that the gauge boson became massive [29]. Away from the fixed points we have: $\langle m \rangle \neq 0$. Restoration of SUSY (that is more economical state for the system) implies that the charged scalars will acquire a non-vanishing VEV. This breaks the global $U(1)_A$ symmetry.

2.1. *Calculation of the bare mass of the anomalous U(1)s*

As we mention above, Green-Schwarz mechanism cancels mixed anomalies due to the exchange of an axionic field. However, this mechanism provides a mass term for the anomalous U(1). This mass can be evaluated by 1-loop string computation.

The mass term lays in the IR closed-sting limit of the annulus and the Möbius diagrams with the insertion of two open string vertex operators (VO) on the boundaries. The corresponding diagrams are an annulus with the VO's on different boundaries, an annulus with the VO's on the same boundary, and a Möbius-strip with the VO's on the single boundary. Finally, the last two diagrams drop in the IR closed string limit due to tadpole cancellation and the mass-term lies in the IR limit of the first diagram [19] and it depends on the internal volumes of the D-brane $\mathcal{V}_D$ where the anomalous U(1) lives onto, and the volumes of the orientifold plane $\mathcal{V}_O$ where the axion is twisted. Schematically:

$$M^2 \ \sim \ {M_s}^2 \frac{\mathcal{V}_{D\cap O}^2}{\mathcal{V}_D \mathcal{V}_O} \tag{2.6}$$

where $\mathcal{V}_{D\cap O}$ the volume of the intersection of the D-bane and the O-plane. Consequently, the masses of the anomalous U(1)'s can be even lower than the string scale M_s.

If the string scale is close to the few TeV, such bosons might be visible in the next experiments at LHC. They will behave almost as Z', with the difference that they might have extra anomaly related coupling that distinguish them from all other Z' models that have been studied in the past.

2.2. *Generalized Chern-Simons: A toy model*

As it was shown [25], the Green-Schwarz mechanism is not enough to cancel all the anomalies in a model. In particular, generalized Chern-Simons terms are necessary to cancel mixed anomalies between anomalous and non-anomalous U(1)s.

In this section, we will concentrate on a toy-model with two U(1)s, one anomalous with gauge field A_μ, field strength $F^A_{\mu\nu}$ and charge operator Q_A, and the other non-anomalous with gauge field Y_μ, field strength $F^Y_{\mu\nu}$ and charge operator Q_Y. $G^a_{\mu\nu}$ denote as before other non-abelian field strengths. In general:

$$Tr[Q_Y]=0\ , \qquad Tr[Q_Y^3]=0\ , \qquad Tr[Q_Y T^a T^a]=0 \tag{2.7}$$

$$Tr[Q_A Q_Y^2]=c_1\ ,\ \ Tr[Q_A^2 Q_Y]=c_2\ ,\ \ Tr[Q_A^3]=c_3\ ,\ \ Tr[Q_A T^a T^a]=\xi \tag{2.8}$$

By definition non-anomalous U(1)'s obey conditions (2.7). However, mixed traces with the non-anomalous U(1) might be different from zero (2.8). This structure can emerge in type I theories after recombining some U(1) factors arising from the 'center of masses' of brane configurations. In particular we have in mind intersecting brane embeddings of (some supersymmetric extension of) the standard models where the non anomalous U(1) Y is a combination of the CP U(1)'s with $Tr[Q_Y]=Tr[Q_Y^3]=0$ but in general $Tr[Q_A Q_Y]\neq 0$.

The above traces imply anomalous transformations of the one-loop effective action. Therefore, under

$$A_\mu \to A_\mu + \partial_\mu \epsilon \quad , \quad Y_\mu \to Y_\mu + \partial_\mu \zeta \tag{2.9}$$

the action transforms as:

$$\delta S_{1-loop} = \int d^4x \left\{ \epsilon \left[\frac{c_3}{3} F^A\wedge F^A + c_2\ F^A\wedge F^Y + c_1\ F^Y\wedge F^Y + \xi\ Tr[G\wedge G]\right] \right.$$
$$\left. + \zeta \left[c_2\ F^A\wedge F^A + c_1\ F^A \wedge F^Y \right] \right\} \tag{2.10}$$

Following Green-Schwarz mechanism, we add the action

$$S_{\rm axion} = \int d^4x \left\{ -\frac{1}{4g_Y^2}(F^Y)^2 - \frac{1}{4g_A^2}(F^A)^2 + (\partial_\mu\alpha + MA_\mu)^2 \right.$$
$$\left. + \alpha \left(d_3\ F^A\wedge F^A + d_2\ F^A\wedge F^Y + d_1\ F^Y\wedge F^Y + d_0\ trG\wedge G\right) \right\} \tag{2.11}$$

where $d_0,\ d_1,\ d_2,\ d_3,\ M$ are constants. The axion α transforms as

$$\alpha \to \alpha - M\epsilon \quad , \tag{2.12}$$

and we are assuming that α does not shift under non-anomalous gauge transformations parameterized by ζ.

It is obvious that the axionic transformation can cancel only terms proportional to ϵ (first line in (2.10)) but not the ones proportional to ζ (second line). Therefore, it is necessary to add not invariant ζ terms, the so called *generalized Chern−Simons* (GCS) terms:

$$S_{\rm GCS} = \int Y \wedge A \wedge \Big\{ d_4\ F^A - d_5 F^Y \Big\} \tag{2.13}$$

where $d_4,\ d_5$ are constants. The gauge variation of the classical action (now $S_{\rm class} = S_{\rm axion} + S_{\rm GCS}$):

$$\begin{aligned} \delta S_{\rm class} = -\int \epsilon\ \Big\{ & d_3\ F^A \wedge F^A + (d_2 - d_4)\ F^A \wedge F^Y + (d_1 + d_5)\ F^Y \wedge F^Y \\ & + d_0\ tr(G \wedge G) \Big\} \\ - \int \zeta\ & \Big\{ d_4\ F^A \wedge F^A - d_5\ F^Y \wedge F^A \Big\}\ . \end{aligned} \tag{2.14}$$

Anomaly cancellation implies:

$$d_0 = \xi \quad , \quad d_1 = 2c_1 \quad , \quad d_2 = 2c_2 \quad , \quad d_3 = \frac{c_3}{3} \quad , \quad d_4 = c_2 \quad , \quad d_5 = -c_1 \quad . \tag{2.15}$$

Notice that, the presence of the generalized CS terms is due to the non-vanishing c_1 and c_2, which are present if there are mixed anomalies between the anomalous and non-anomalous U(1)'s.

This is a generic situation. Anomalous and non-anomalous factors usually appear in open string models. The presence of GCS terms is necessary to cancel all the anomalies [25].

2.3. *Generalized Chern-Simons terms and anomaly free gauge theories*

Generalized Chern-Simons terms are present in any anomaly free gauge theory, where spontaneous symmetry breaking gives heavy and light fermions. Effectively, in energies lower than the heavy fermionic masses, we have a model with anomalies which are cancelled by axionic and generalized Chern-Simons terms.

Therefore, consider a consistent (*i.e.* anomaly-free) and renormalizable gauge theory with spontaneously-broken gauge symmetry via the Brout-Englert-Higgs mechanism. Through appropriate Yukawa couplings, some large masses can be given to a subset of the fermions. Absence of anomalies requires that

$$\sum_{\rm light+Heavy} (Q_L^i Q_L^j Q_L^k - Q_R^i Q_R^j Q_R^k) \ = \ 0$$

where $Q_i{}'$s denote the charge operators of the various U(1)$'$s. In general, the previous sum evaluated only for the light fermions is different from zero, generating a superficially anomalous EFT at a lower scale than the heavy fermion mass M_H.

In addition, consider a Higgs-like field $H = (v + h)e^{i\alpha/v}$ where $\langle H \rangle = v$ and α transforms as an axion $\delta\alpha = v\epsilon$. It has been shown that the decoupling of heavy chiral fermions by large Yukawa couplings does generate a generalized Green-Schwarz mechanism at low energy, with axionic couplings cancelling anomalies of the light fermionic spectrum in combination with generalized Chern-Simons terms which play an important role in anomaly cancellation (figure 1) [25].

Consequently, GCS-terms are a prediction of any anomaly-free chiral gauge theory with light and heavy fermions and it seems that we cannot distinguish between low-energy predictions of string theory versus 4d field theory models. However, a deeper analysis is needed in this direction.

3. D-brane Standard Model and Generalized Chern-Simons terms

In this section, we provide a D-brane configuration that can describe the Standard Model and we argue that generalized Chern-Simons terms provide new couplings with specific phenomenological interest.

The ten-dimensions of string theory are split into four flat non-compact and six compact dimensions. D-branes are inserted and they are longitudinal to the four non-compact dimensions. In addition, there are Orientifold planes which are non-dynamical hyperplanes that change the orientation of the strings and they are essential for the consistency and the stability of the theory [30]. Since open strings are proportional to their lengths, the branes that give rise to the SM must be very close together in the internal space. Therefore, we can focus in this particular area since all other branes further away may affect the global (the stability and consistency of the configuration) rather than the local properties of the model. These are called the $bottom - up$ approaches.

If the end of a string is attached on a stack of m branes it can take m different values. It is easy to see that an oriented string with both ends on the same stack of branes can take $m \times m$ values and transforms in the Adjoint of an U(m) group. We can split U(m)≡SU(m)×U(1)$_m$ where the index m in the U(1) denotes that the abelian factor is coming from the m-stack of branes. An oriented string which starts from an m and ends on an n stack transforms in the bifundamental $(m, \bar{n}) \equiv (m, 1_m; \bar{n}, -1_n)$ in the two representations. As we mentioned before, unoriented strings are those which pass through an O-plane. Therefore, we can have unoriented

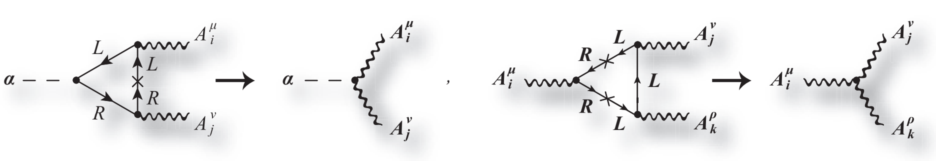

Fig. 1. We denote by L, R the left, right fermions respectively and by $\times$ the heavy mass insertion. Integrating out the heavy fermions, we obtain the axionic and the generalized Chern-Simons terms.

strings which transform as $(m,n) \equiv (m,1_m;n,1_n)$ or $(\bar{m},\bar{n}) \equiv (\bar{m},-1_m;\bar{n},-1_n)$. Finally, unoriented strings with both ends on the same stack of branes transform in the antisymmetric or symmetric representation of U(m), depending on the O-plane: $\genfrac{}{}{0pt}{}{\square}{\square}_m \equiv (\genfrac{}{}{0pt}{}{\square}{\square}_m, 2_m)$ and $\square\square_m \equiv (\square\square_m, 2_m)$.

Keeping all these in mind, we can study D-brane configurations that describe the SM spectrum which contains:

$$3 \times \left[Q\ (3,2,\frac{1}{6}) + u^c\ (3^*,1,-\frac{2}{3}) + d^c\ (3^*,1,\frac{1}{3}) + L\ (1,2,-\frac{1}{2}) + l^c\ (1,1,1) \right]$$

and in addition, three left-handed anti-neutrinos ν^c in the representation $(1,1,0)$, and three MSSM Higgs pairs, $H\ (1,2,\frac{1}{2}) + H'\ (1,2,-\frac{1}{2})$.

We will focus our interest in a group of four stacks of branes that could describe the Standard Model spectrum. One stack contains three branes and we will call it the "color" branes since they provide an SU(3)$\times$U(1)$_3$ group. The second stack consists of two branes and we will call them the "weak" branes since they provide an SU(2)$\times$U(1)$_2$ group. The rest of the stacks consist of single branes and each provide a U(1) factor. Therefore, there are four abelian factors from which one linear combination is anomaly free and represents the hypercharge and the rest are in general anomalous.

In such configuration, the Q's are described by strings which are stretched between the color and the weak branes. The u's and d's are stretched between the color and the different single branes. The L's are stretched between the weak and one of the single branes and the l's are stretched between the single branes. In addition, the Higgses H_u and H_d are stretched between the weak and the single branes.

There are many different combinations of string states that can describe the Standard Model, depending on the orientation of the strings. However we will focus in one specific example with:

$$Q\ \ (+1,-1,0,0) \tag{3.16}$$
$$u\ \ (-1,0,-1,0) \tag{3.17}$$
$$d\ \ (-1,0,0,-1) \tag{3.18}$$
$$L\ \ (0,+1,0,-1) \tag{3.19}$$
$$l\ \ (0,0,+1,+1) \tag{3.20}$$
$$H_u\ \ (0,+1,+1,0) \tag{3.21}$$
$$H_d\ \ (0,-1,0,-1) \tag{3.22}$$
$$\nu\ \ (0,0,0,+2) \tag{3.23}$$

where the four numbers in the parenthesis denote the charges (Q_3, Q_2, Q_1, Q_1') of the open strings under the color, the weak, and the two single branes respectively. In this case, the hypercharge is given by $Y = -\frac{1}{3}Q_3 - \frac{1}{2}Q_2 - Q_1'$, the baryon number by $B = \frac{1}{3}Q_3$, the lepton number by $L = \frac{1}{2}(Q_3 + Q_2 - Q_1 - Q_1')$ and the Peccei-Quinn by $PQ = -\frac{1}{2}(Q_3 - Q_2 - 3Q_1 + 3Q_1')$.

We can easily realize that only the hypercharge Y is free of anomalies. Therefore, apart from the SM particles, we have three more U(1)'s, three axions that mix with the U(1)'s and three pairs of Higgs doublets.

Next, we would like to diagonalize the mass matrix of the U(1)'s and go to the so called *photon basis*. There are two mass-origins for the U(1)'s. One is the electroweak symmetry breaking and the other the Stückelberg anomaly-related terms [24]:

$$|\mathcal{D}_\mu H_u|^2 + |\mathcal{D}_\mu H_d|^2 + \frac{1}{2}\sum_I (\partial \alpha_I + M_I A_I)^2 \tag{3.24}$$

where $\mathcal{D}_\mu H_u = \left(\partial_\mu + \frac{i}{2} g_2 \tau^\alpha W^\alpha_\mu + \frac{i}{2} g_Y A^Y_\mu + \frac{i}{2}\sum_I q^I g_I A^I_\mu\right) H_u$ (similarly for H_d). Index I spans on the three anomalous U(1)'s. We should mention that the Higgses are charged only under Y and PQ and after electroweak symmetry breaking only Y and PQ are spontaneously broken. Therefore:

- The photon A, the Z^0 and the PQ-related Z'-boson are the three eigenstates of the mass matrix of Y, PQ and W_3. This change of basis

$$\begin{pmatrix} W^3 \\ Y \\ PQ \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & \mathbf{c_{13}} \\ c_{21} & c_{22} & \mathbf{c_{23}} \\ \mathbf{c_{31}} & \mathbf{c_{32}} & c_{33} \end{pmatrix} \begin{pmatrix} A \\ Z^0 \\ Z' \end{pmatrix} \tag{3.25}$$

  where

$$c_{11}, c_{12}, c_{21}, c_{22}, c_{33} \sim \mathcal{O}(1) \quad , \quad \mathbf{c_{13}}, \mathbf{c_{23}}, \mathbf{c_{31}}, \mathbf{c_{32}} \sim \mathcal{O}\left(M_Z^2/M_s^2\right) < 10^{-4} \tag{3.26}$$

- On the other hand the B and L gauge bosons are not affected by the Higgs mechanism. They give two extra massive Z' gauge bosons with masses proportional to the string scale M_s.

As we have argued in section 2.2, generalized Chern-Simons terms are necessary to cancel all the anomalies, since the above models contain anomalous and non-anomalous U(1)'s. Consider for example $PQ \wedge Y \wedge dY$, which after a rotation to the photon basis it generates various anomaly cancelling Chern-Simons-like terms:

$$PQ \wedge Y \wedge dY \longrightarrow \begin{cases} Z^0 \wedge A \wedge dA & \Rightarrow \quad Z^0 \to \gamma\gamma \quad \sim \quad \mathcal{O}\left(M_Z^2/M_s^2\right) \\ A \wedge Z^0 \wedge dZ^0 & \Rightarrow \quad Z^0 \to Z^0\gamma \quad \sim \quad \mathcal{O}\left(M_Z^2/M_s^2\right) \\ Z' \wedge A \wedge dA & \Rightarrow \quad Z' \to \gamma\gamma \quad \sim \quad \mathcal{O}(1) \\ Z' \wedge Z^0 \wedge dZ^0 & \Rightarrow \quad Z' \to Z^0 Z^0 \quad \sim \quad \mathcal{O}(1) \\ Z' \wedge Z^0 \wedge dA & \Rightarrow \quad Z' \to Z^0\gamma \quad \sim \quad \mathcal{O}(1) \end{cases} \tag{3.27}$$

We should mention that some decays vanish on-shell. However, $Z' \to Z\gamma$ and $Z' \to ZZ$ produce new signals that distinguish such models from other Z' models. If the string scale is of order of a few TeV, such signals may be visible in LHC.

4. Conclusions

As we have mentioned, all open string models that approach the Standard Model contain anomalous U(1) gauge fields. The anomaly is cancelled via the Green-Schwarz mechanism that generates a mass for the corresponding anomalous gauge boson.

However, Green-Schwarz mechanism is not enough to cancel all the anomalies. Mixed abelian anomalies between anomalous and non-anomalous factors need generalized Chern-Simons terms to be cancelled.

Next, we provide a D-brane model that describes the Standard Model and apart from the hypercharge it contains three additional abelian factors which are anomalous. It also contains three axions and three pairs of Higgs doublets. The presence of anomalous and non-anomalous U(1)'s requires generalized Chern-Simons terms. These anomaly related couplings produce new signals that distinguish such models from other Z' models. If the string scale is of order of a few TeV, such signals may be visible in LHC.

Acknowledgments

The author would like to thank Massimo Bianchi, Emilian Dudas and Elias Kiritsis for the fruitful collaboration. It is a pleasure to thank the organizers of the organizers of the international symposium on "Supersymmetry at LHC: Theoretical and Experimental Prospectives" in Cairo 11-14 March 2007 for giving the opportunity to present this work. This work was supported in part by INFN, by the MIUR-COFIN contract 2003-023852, by the EU contracts MRTN-CT-2004-503369 and MRTN-CT-2004-512194, by the INTAS contract 03-516346 and by the NATO grant PST.CLG.978785.

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