Relaxing Cosmic Censorship and Chronology Protection conjectures

Dmitry V. Gal'tsov

Moscow State University

In collaboration with
Gerard Clement and
Mourad Guenouch

Ginzburg Centennial Conference on Physics
Lebedev Institute / Moscow
May 29 – June 3 2017

Content

- Why
- Taub-NUT
- Misner string does not stop geodesics
- Wormhole-catalysis with NUT
- Gamma-metric
- Tomimatsu-Sato 2
- Almost regular stationary two-black hole solution

Why?

- **Black hole theory is beautiful!**
- **But suffers from Brezhnev's syndrome (stagnation)!**
- **Too boring monotony of black holes (Kerr uniqueness) in comparison with the diversity of other physical world**
- **To go beyond the standard BH theory:**
  1. **To modify gravity (radical)**
  2. **To violate energy conditions within Einstein gravity (less radical)**
- **Here: To preserve 1 and 2, but modify basic assumptions:**

  Cosmic censorship

  Chronology protection

Beyond Kerr

- **Current understanding of the final stage of gravitational collapse in General Relativity (GR) is based on singularity, no-hair and uniqueness theorems which suggest Kerr metric as a unique metric for a single black hole** (Penrose, Hawking, Israel, Carter, Robinson…)

- **This picture is robust, but still susceptible to possible modifications of GR and to changes in key assumptions such as *cosmic censorship* (CC)** (Penrose) **and *chronology protection* (CP)** (Hawking) **which are plausible but not proven rigorously.**

- **In anticipation of the Event Horizon Telescope data one is interested in alternatives to Kerr. Popular poposals like "bumpy BH" or "modified Kerr"** (Psaltis, Bambi..) **suffer from naked singularities (NS) and/or presence of closed time-like curves (CTC), which are usually regarded as pathologies.**

The purpose of this talk is to discuss whether NS and CTC are always pathologies

Infinitely thin cosmic strings

- **Conical singularity which stops geodesics --- i.e. genuine singularity**
- **Can be seen from infinity --- i.e. naked singularity**
- **Ricci tensor has 2d delta-function singularity**
- **But can be easily regularized adding some acceptable matter --- example of acceptable naked singularities**

NUT-ty space-times

Taub-NUT metric can be viewed as BH endowed with the magnetic mass n; it was identified by Misner (‘63) as stationary patch of the cosmological solution of Taub:

$$ds^2 = -f(dt - 2n(\cos\theta + C)\, d\varphi)^2 + f^{-1}dr^2 + \rho^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

Here $f = (r^2 - 2rm - n^2)/\rho^2$, $\rho^2 = r^2 + n^2$

C is parameter, corresponding to ‘large’ coordinate transformation $t \to t + C\varphi$

Does not contain central curvature singularity (like gauge monopoles), but polar axis has a problem (Misner string, MS)

MS is at North semiaxis for C=1, at South semiaxis for C=-1, and at full axis for C=0. Solution is not AF, but ALF. Has an event horizon, but regular at r=0

Dirac string for magnetic monopole is unobservable if electric charge is quantized (periodic phase of the wave-function). Likewise, MS can be made unobservable if the energy is quantized (Mueller and Perry ’86)**, but this demands compactification of time with the period 8 pi n** (Misner)**.**

Compact time is reasonable in Euclidean sector, where TaubNUT is regular instanton (Hawking 1970). **But in Lorentzian sector this means presence of CTCs at any point of space. But without periodicity condition MS was regarded as physical sigularity (stopping geodesics).**

WHY NUT ?

- **Strongly predicted by supergravities (dualities)**
- **`Exotic matter'**
- **One of most natural non-Kerr vacuum solutions, has peculiar geodesic oribits (helical) distinguishable in lensing observations. Though usually rejected as unphysical by theoreticians, nevertheless attracted attention in astrophysics (Nouori-Zonos and Lynden-Bell '97,Ravhar and Habibi '04, Bogdanov and Cherepashchuk '08…)**
- **Can be viewed as the end of the Misner string, like magnetic monopole --- the end of semi-infinite solenoid**
- **Euclidean Taub-NUT is finite action gravitational instanton --- possibly mediating quantum creation of BH-s with NUT**
- **Possibility of NUT- anti NUT pairs without infinite MS**

Refusing of time periodicity, one has to explore MS more closely. (earlier: Zimmerman and Shahrir, 1988). **Apart of** $K_{(t)} = \partial_t$**, TN metric still have so(3) Killing vectors**

$$K_{(\pm)} = K_{(x)} \pm iK_{(y)} = \mathrm{e}^{\pm i\varphi}\left(\pm i\partial_\theta - \cot\theta\,\partial_\varphi - \frac{2n(1+C\cos\theta)}{\sin\theta}\,\partial_t\right),$$
$$K_{(z)} = \partial_\varphi + 2nC\,\partial_t\,,$$

so TN spacetime is separable in Carter's sense. Four geodesic integrals are

$$E = \left(\dot{t} - 2n(\cos\theta + C)\dot{\varphi}\right) f\,,$$
$$J_\pm = J_x \pm iJ_y = \left(2nE\sin\theta - \rho^2(i\dot{\theta} - \sin\theta\cos\theta\dot{\varphi})\right)\mathrm{e}^{\pm i\varphi}\,,$$
$$J_z = 2nE\cos\theta + \rho^2\sin^2\theta\dot{\varphi}\,,$$

Angular motion is described analytically: $\cos\theta = J^{-2}\left[2nEJ_z + lJ_\perp\cos(J\lambda)\right]$

$$\varphi - \varphi_0 = \arctan\left[\frac{\cos\psi - \cos\eta}{1-\cos(\psi-\eta)}\tan\frac{J\lambda}{2}\right] + \arctan\left[\frac{\cos\psi + \cos\eta}{1+\cos(\psi-\eta)}\tan\frac{J\lambda}{2}\right]$$

with $J^{-2}\left(2nEJ_z \pm lJ_\perp\right) = \cos(\psi \mp \eta)$ **North polar axis is crossed if** $J_z = 2nE$ **then**

$$\cos(\varphi - \varphi_1) = \frac{J_z}{J_\perp}\tan\left(\frac{\theta}{2}\right)$$

Clearly, polar axis is traversed in fully smooth way.

Thus, Misner string is not a singularity. Moreover, since time periodicity is not imposed, the TN metric can be analytically continued through the horizons without Hausdorff problem. Absence of the central curvature singularity then means that Taub-NUT geometry is fully regular ! ***(G.Clement, D.G. and M.Guenouch, 2015)***

Distributional curvature

- **Distributional curvatures may be introduced for defects embedded in space with codimension one (domain walls) and two (strings)**

- **Conical singilarity in cosmic string metric generates distributional Ricci tensor proportional to two-dimensional delta-function in the plane, orthogonal to the string** (Marder ’58, Starushckievich ’63, Deser et al ’84, Clarke et al ’96)**.**

- **Inverse is not true: 2d delta-function in Ricci tensor does not always imply cones, whose source is stress-tensor with tension equal to mass density (both for positive and negative mass). MS corresponds to negative mass density and has no tension, so it does not produce conical singularity.**

- **An important consequence is that while geodesics are stopped at conical singularities, they are not stopped at MS. Still it is worth noting that not any distributional singularity is geodesically traversable, a counter example being the cosmic string.**

More about magnetic mass

What is physical nature of NUT parameter? By analogy with magnetic monopole, it can be viewed as dual (magnetic) mass. Since TN solution does not contain central singularity, the NUT parameter looks as charge without charge (topological); tentatively such objects could be produced by breaking MS created as topological defects in the early universe as result of breaking of SO(3) spatial symmetry in favor of non-trivial S1 bundle. The required matter underlying MS is worth to be explored more closely. Note that NUT-anti NUT pairs joined by MS would be similar to monopole-antimonopole joined by cosmic string.

- **It is interesting to note that the distributional stress tensor of MS with small n is somewhat similar to that of "giraton", proposed by Frolov and Israel (boosted to the infinite momentum frame)**

Weak chronology protection

Another problem of Taub-NUT is CTC-s. Rewrite the metric in ADM form:

$$ds^2 = -\frac{f\rho^2\sin^2\theta}{\Sigma}dt^2 + f^{-1}dr^2 + \rho^2 d\theta^2 + \Sigma\left(d\varphi + \frac{2nf(\cos\theta + C)}{\Sigma}dt\right)^2$$

where $\Sigma(r,\theta) = \rho^2\sin^2\theta - 4n^2 f(\cos\theta + C)^2$ **. For** $f(r) < 0,\ \Sigma$ >0

while for $f(r) > 0$ **it becomes negative in some vicinity of MS, so CTCs.**

But these are not geodesic (G.Clement and D.G. 2015)

$$\Delta t = \Delta t_r + \Delta t_\theta \geq \frac{2\pi}{E}\left[J - 2nE - \varepsilon n^2/J\right]$$ **RHS can be shown to be positive**

both for time-like and null geodesics provided $|C| \leq 1$**.Thus CTC-s are harmless for free classical observer. Weak chronology protection allowing for non-geodesic CTC can be suggested to replace the usual CP prohibiting any CTC. The idea behind this proposal is that in order to convert non-geodesic CTCs into time-machine one has to switch on the 'engines' which presumably will modify solution eliminating CTCs.**

This was generalized to charged particles moving in charged NUTty backgrounds According their EOMs (G. Clement and M. Guenouch, 2017)

Transforming naked singularities to wormholes using NUT

G.Clement and DG '15

Regularizing property of NUT can be used to convert naked singularity of supercritical Reissner-Nordstrom solution to wormhole

$$ds^2 = -f(dt - 2n(\cos\theta + C)\,d\varphi)^2 + f^{-1}dr^2 + (r^2+n^2)(d\theta^2 + \sin^2\theta d\varphi^2)$$

$$A = \Phi(dt - 2n(\cos\theta + C)\,d\varphi)\,,$$

where now

$$f = \frac{(r-m)^2 + b^2}{r^2+n^2}\,, \quad \Phi = \frac{qr + p(r^2-n^2)/2n}{r^2+n^2}$$

$$(b^2 = q^2 + p^2 - m^2 - n^2)\,.$$

Again MS is geodesically traversable and CTCs surrounding it can not be transformed into time machine even considering non-geodesic 'charged' observers (G.Clement and M.Guenouch, 2017)

Thus, NUT helps to avoid strong curvature singularities, but generates weak Misner strings whose most undesirable feature is infiniteness, since they possess finite linear density of angular momentum, so the total momentum is infinite (Bonnor, Manko and Ruiz '06). **Further idea of engineering more appropriate solutions will be taking NUT-anti NUT pairs joined by MS**

Gamma-metric

- **Gamma – metric is (very bad) candidate for non-Kerr alternative** (Bach and Weyl 1922, Darmois '27, Zipoy '66, Voorhees '70, an extensive review of Weyl solutions can be found in Griffiths and Podolski's book 2009)

$$ds^2 = \left(1 - \frac{2m}{r}\right)^{\gamma} dt^2 - \frac{1}{(1 - 2m/r)^{\gamma}} \left[\left(\frac{r^2 - 2mr}{r^2 - 2mr + m^2 \sin^2\theta} \right)^{\gamma^2 - 1} dr^2 + \frac{(r^2 - 2mr)^{\gamma^2}}{(r^2 - 2mr + m^2 \sin^2\theta)^{\gamma^2 - 1}} d\theta^2 + (r^2 - 2mr) \sin^2\theta \, d\phi^2 \right]$$

- **This describes Schwarzschild BH for gamma=1 and have regular horizons for higher integer values of this parameter, when it is interpreted as system of two black holes held apart by a rod which is naked singularity of positive mass. For non-integer values r=2M is strong curvature naked singularity of different nature: pointlike for negative gamma, string-like on the interval (0,1), and ring-like for higher values** (Kodama and Hikida '03)**.**

- **Gamma-metric became popular as a model of deformed BH as well as the starting point for further generalizations. It has only two Killing symmetries and is Carter-nonseparable. Geodesic motion generically is chaotic**

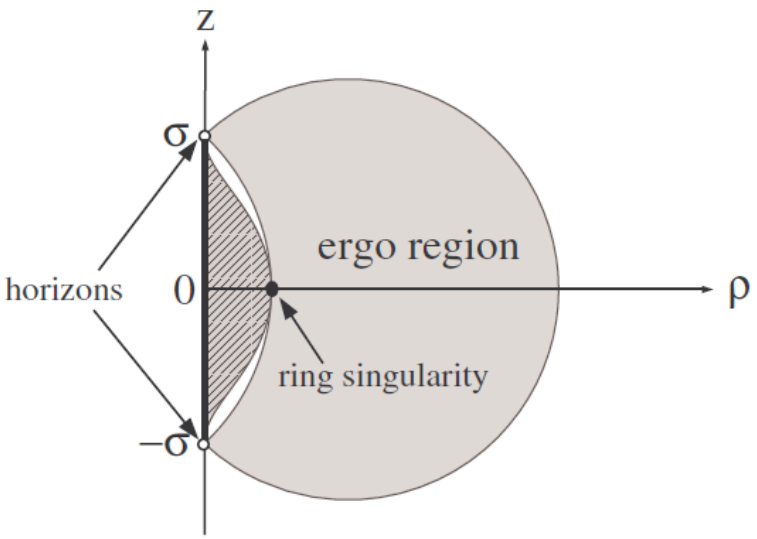
Tomimatsu-Sato solution

This is the rotating generalization of gamma-metric which has only conical singularity on the axis, but contains a strong ring curvature singularity in the equational plane.

It has ergo region and the CTC region which is not inside the ergosphere, the ring singularity is their common point.

The ends of the rod are horizons with zero surface gravity (extreme BHs)

So rotation improves singular behavior of gamma-metrics, but the ring naked singularity in unfortunate



Clement solution (1998)

- **From all rotating generalizations of gamma-metric, this one is the most interesting physically and contains minimum of undesirable features. It can be considered as special rotating and charged generalization of the gamma-metric.**

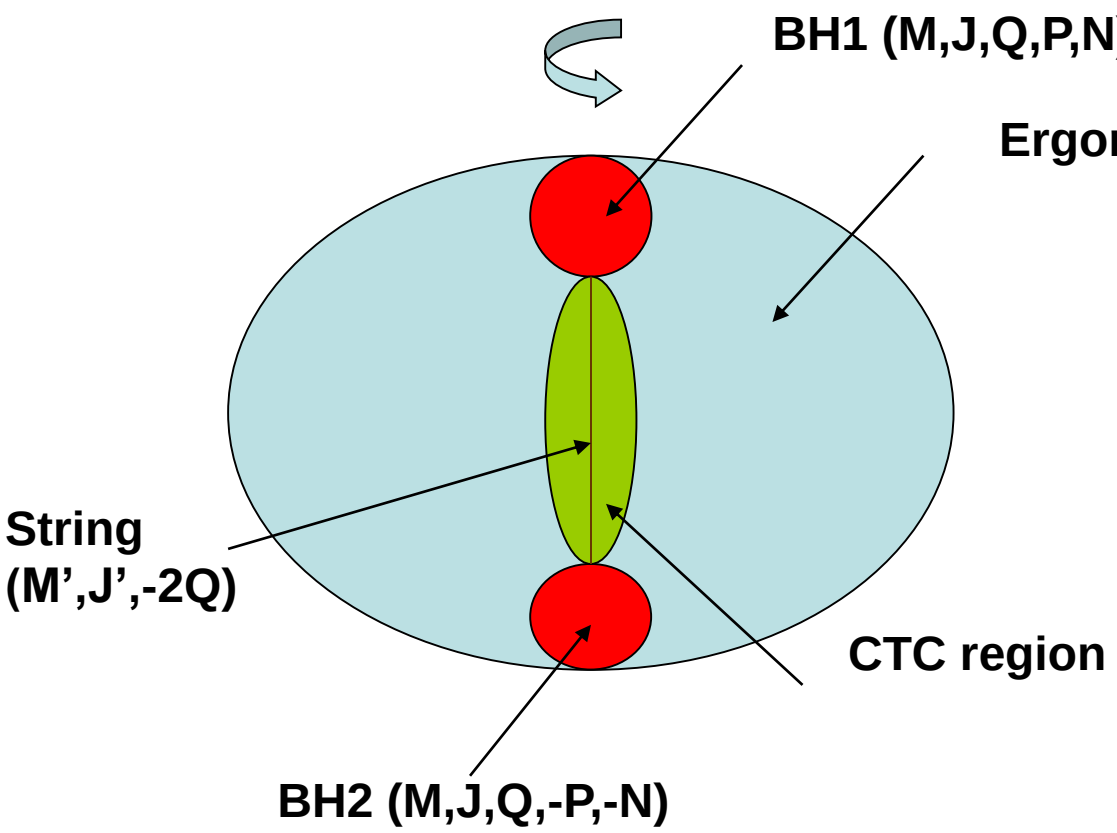
- **It was obtained via original Clement's generating technique applicable to Einstein-Maxwell system which makes explicit the original Geroch idea of combining sigma-model symmetries for different Killing vectors used in dimensional reduction. It produces one-parametric stationary solution of the EM system from a static vacuum solution with certain relation between rotational and electromagnetic properties.**

- **The Clement-transformed gamma-metric is a rotating solution which can be interpreted as the system of co-rotating dyons with equal electric and opposite magnetic charges, also endowed with opposite NUT charges. It does not have ring-like singularity of TS type, while the non-causal region lies inside the ergosphere. There are no CTCs in the frame co-rotating with the horizon.**

From all known solutions it seems to be the best candidate for ECO-s with mild violation of cosmic censorship

Two dyonic NUT-ty extreme BH-s on a string (G.Clement 1998)

String is distributional naked singularity: conical defect+Misner string+Dirac string



Solution is AF endowed with mass, angular momentum, magnetic moment and electric quadrupole moment

No strong curvature singularities

String not seen from infinity

No CTCs in corotating frame

(G.Clement and D.G. 2017)

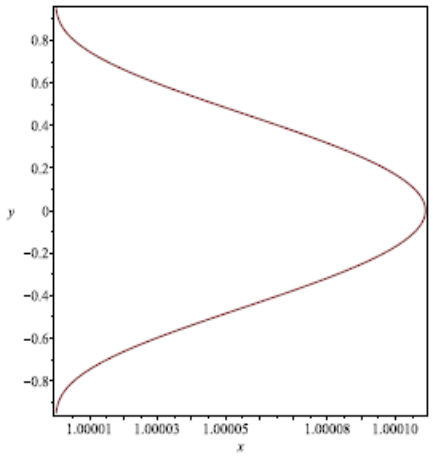
String is electrically charged and magnetized

Remarkable regularity features of Clement's solution is due to fine tuning of parameters: mass, angular momentum and magnetic moment

$$M = \frac{2\kappa}{p}, \quad J = -\frac{\kappa^2 q(4+p^2)}{p^2}, \quad \mu = \varepsilon\kappa^2 q$$

where $p^2 + q^2 = 1$ **, satisfying Kerr-like relation J/M^2 <1 and Barrow-Gibbons (2017) conjecture mu/J<1, actually 1/5**

$$M^4 = \frac{(J+|\mu|)^3}{J+5|\mu|}$$



The electric charges are: $Q_+ = Q_- = -\frac{\varepsilon\kappa(1+p)}{2}$

Magnetic charges: $P_\pm = \pm\frac{\varepsilon\kappa\gamma(p)}{2q}$

NUT charges: $N_\pm = \pm\frac{\kappa\lambda(p)}{4q}$

$$\lambda_+(p) = \frac{(1+p)(8-4p+5p^2-p^3)}{2p} \qquad \gamma_+(p) = \frac{(1+p)(4-p+p^2)}{p}$$

Summarizing the features of the solution, we can present it schematically as a system of two extreme co-rotating black holes endowed with masses, NUT charges, electric and magnetic charges held apart by a magnetized, electrically charged string of negative tension, which is also a Dirac and Misner The whole system lies inside the ergosphere. As the Misner string does not extend to infinity, the solution is asymptotically flat. There are no strong curvature singularities, while the string, which can formally be considered as a mild naked singularity, is inaccessible from infinity. The charges compensate each other so that the asymptotic parameters are the mass, the angular momentum and the gravitational and electromagnetic multipole moments. The family interpolates between the static vacuum ZV2 solution for $q = 0$ and extreme Kerr for $q = 1$. As usual, the Misner string is surrounded by a region containing CTCs. As we have argued before, NUT-related CTCs do not necessarily lead to observable violations of causality.

This solution can be analytically continued beyond the horizons. The most economical maximal analytical extension contains two interior regions between an outer and an inner horizon (both degenerate), and beyond the inner horizons a third region extending to spacelike infinity and containing a timelike ring singularity.

Comparing with other known stationary solutions describing two-black hole systems, we think that this one has a minimal number of physically undesirable features and can be considered as "almost" physical.

Lessons

- **Misner strings in NUT-ty metrics without time identification are not singularities (geodesics do not stop there)**

- **Closed time-like curves around MS are not geodesic. No distant observer can transform MS into time-machine. These two features suggest weak version of Cosmic censorship and Chronology protection conjectures**

- **Adding NUT charge to a naked singularity may transform it to wormhole without violation of energy conditions apart from the Misner string (super-extreme Reinssner-Nordstrom). Non-causal region around MS does not produce CTCs either for neutral (geodesics) or for charged particles**

- **Suitably tuning charges including NUTs one gets rotating two-black hole system joined by a string (cosmic+MS+DS) without strong naked singularities and only a tiny CTC region around the string inside the ergosphere. The solution still satisfies some standard BH properties and provides an example of non-Kerr solution with mild violation of CC and CP conjectures.**