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ANALOGIES, NEW PARADIGMS, AND OBSERVATIONAL DATA AS GROWING FACTORS OF RELATIVISTIC ASTROPHYSICS

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Patterns in the scientific development of relativistic astrophysics are analyzed with special attention to the physics and astrophysics of black holes and gamma-ray bursts.

1 Introduction

Hagen Kleinert has been a pioneer in establishing analogies among widely separated fields of theoretical physics, applying relativistic quantum field theoretical techniques, notoriously his classical work with Richard Feynman [1], to the treatment of a variety of research topics ranging from condensed matter to crystal melting, polymer physics, phase transitions, differential geometry etc. I have always been very impressed by his profound knowledge of physics and his courage in approaching so vast a research program, as testified also in his classical books [2–4]. On the occasion of his sixtieth birthday, I am dedicating to him a few brief considerations based on my work, of how the role of analogies among different fields, the establishment of new paradigms, as well as the crucial and timely arrival of observational data have marked the development of relativistic astrophysics.

2 The Birth of Relativistic Astrophysics

In 1931, in analogy with the development made in the field of atomic physics by Enrico Fermi and his school [5], Lev D. Landau [6] was led to introduce

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a new paradigm in the approach of astrophysical problems. This was not based on a hypothesis chosen merely for mathematical convenience, but was founded on new concepts developed in theoretical physics. Using the Fermi-Dirac statistics to study the equilibrium of a star paved the way to analyze the latest phases of the evolution of a star. This approach has developed into an entirely new theory for understanding white dwarfs in the classical book by Chandrasekhar [7]. Subsequently, new concepts were introduced by Julius Robert Oppenheimer, using the general relativistic techniques by Tolman and the seminal ideas of George Gamow (with whom Hagen Kleinert studied from 1965 to 1967 while working on his Ph.D. thesis). I recall here the treatment of neutron stars in the classic work with Oppenheimer's student Volkoff [8]. This entire research field reached full maturity with the discovery of pulsars in 1968, especially with the discovery of the crab nebula pulsar. The observation of the period of that pulsar and his rate of slowing-down gave clear evidence for identifying the first neutron star in the galaxy. It also confirmed our understanding that the energy source of pulsars was simply the rotational energy of the neutron star. The year 1968 can definitely be considered as the date of birth of relativistic astrophysics.

I was in Princeton in those days, initially at the university as a postdoctoral fellow in the group of John Archibald Wheeler, later as a member of the Institute for Advanced Study, and finally as an instructor and assistant professor at the university. The excitement about the neutron star discovery boldly led us directly to a yet unexplored classic paper by Oppenheimer and Snyder: *On Continued Gravitational Contraction* [9]. This opened up an entire new research field to which I have dedicated all the rest of my life and which is giving, still today, some distinctively important results. I will comment in the following on a few crucial moments, the way I remember them, that influenced very much the development of relativistic astrophysics, with particular emphasis on the establishment of analogies, new paradigms and crucial observational data.

3 Analogies Between Trajectories of Cosmic Rays and Trajectories in General Relativity

An "effective potential" technique had been used very successfully by Carl Størmer in the 1930s for studying the trajectories of cosmic rays in the earth's magnetic field [10]. In the fall of 1967, Brandon Carter visited Princeton and presented his remarkable mathematical work leading to the separability

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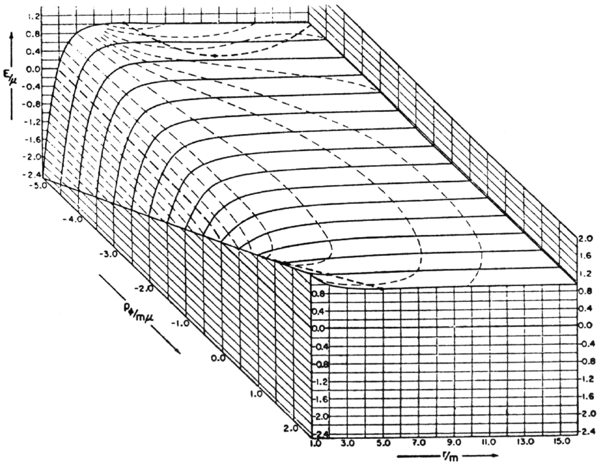

Figure 1. "Effective potential" around a Kerr black hole (reproduced from Ref. [13]).

of the Hamilton-Jacobi equations for the trajectories of charged particles in the field of a Kerr-Newmann geometry [11]. Carter's visit had a profound impact on our small group working with John Wheeler on the physics of gravitational collapse. Indeed, it was Johnny who had the idea to exploit the analogy between the trajectories of cosmic rays and the trajectories in general relativity, using Størmer's "effective potential" technique in order to obtain physical consequences from the set of first-order differential equations obtained by Carter. I still remember my preparing the $2m \times 2m$ grid plot of the effective potential for particles around a Kerr metric which finally appeared in print [12] (see Fig. 1). From this work came the celebrated result of the maximum binding energy of $1 - 1/\sqrt{3} \sim 42\%$ for corotating orbits, and $1 - 5/3\sqrt{3} \sim 3.78\%$ for counterrotating orbits in the Kerr geometry. We were very pleased to be associated with Brandon Carter in a "gold medal" award for this work presented by Yevgeny Lifshitz: in the last edition of Vol. 2 of the Landau and Lifshitz series, entitled *The Classical Theory of Fields*, both Brandon's and my work with Wheeler are mentioned as exercises for bright students! This was certainly a simple and fruitful analogy which led to a successful theoretical accomplishment, opening up a new window on completely unexpected general relativistic effects. It is interesting that it has become clear in recent years that the difference in the binding energies

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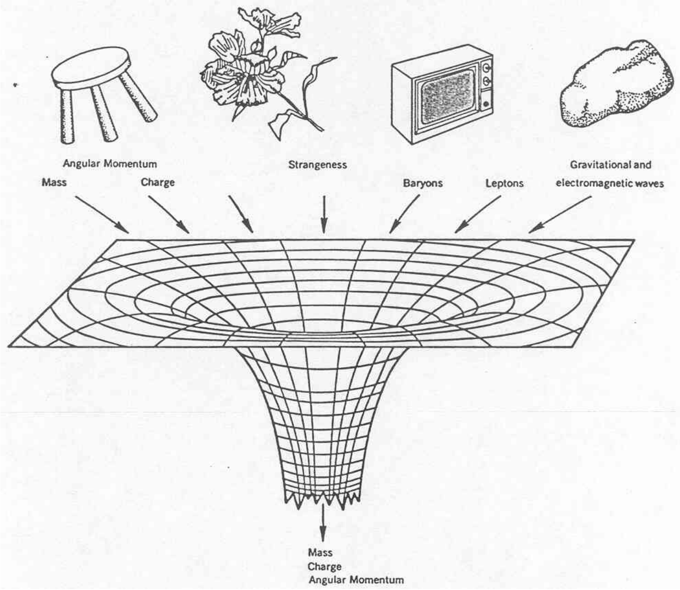

Figure 2. The black hole uniqueness theorem.

of the corotating and counterrotating orbits in a Kerr-Newmann geometry have become the object of direct astrophysical observations in binary X-ray sources.

4 Analogy of "Black Hole" with Elementary Physical System

In my 1971 article in *Physics Today* with Wheeler, entitled *Introducing the Black Hole*, we first proposed the famous "uniqueness theorem" stating that black holes can be completely characterized by their mass-energy E, charge Q, and angular momentum L [13]. This analogy between a black hole and a most elementary physical system was magnificently represented by Johnny in an unconventional figure in which TV sets, bread, flowers, and other objects loose their characteristic features and merge in the process of gravitational collapse into the three fundamental parameters of a black hole (see Fig. 2). That picture became the object of a great deal of light-hearted discussion in the physics community. A proof of this uniqueness theorem, satisfactory for some astrophysical cases, has been obtained after twenty five years of metic-

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ulous mathematical work (see e.g. Regge and Wheeler [14], Zerilli [15,16], Teukolsky [17], Lee [18], and Chandrasekhar [19]). However, the proof still presents some outstanding difficulties in its most general form. Possibly, some progress will be reached in the near future with the help of computer algebraic manipulation techniques to overcome the extremely difficult mathematical calculations (see e.g. Cruciani [20], Cherubini and Ruffini [21], and Bini *et al.* [22,23]).

It is interesting that this proposed analogy, which appeared at first to be almost trivial, turned out to be one of the most difficult to be proven, implying a monumental work unsurpassed in difficulty, both in mathematical physics and relativistic field theories. An extremely good example of the difference between general relativity and classical physics is offered by the face that this analogy is still unproven and that the most general perturbation of a black hole endowed with electromagnetic structure (EMBH) and rotation is still far from being solved. The solution of this problem from a mathematical physics point of view may have profound implications on our understanding of the fundamental physical laws.

5 Analogy Between Pulsars and Black Hole Physics: The Extraction of Rotational Energy

We were still under the sobering effects of the pulsar discovery and the very clear explanation by Tommy Gold and Arrigo Finzi that the rotational energy of the neutron star had to be the energy source of the pulsar phenomenon, when the first meeting of the European Physical Society took place in Florence in 1969. In a splendid talk, Roger Penrose [24] advanced the possibility that, much like in pulsars, the rotational energy could be in principle extracted in black holes. The first specific example of such an energy extraction process was given in a gedanken experiment using the above mentioned effective potential technique by Ruffini and Wheeler [25] (see Fig. 3), and later by Floyd and Penrose [26]. The reason for showing this figure here is a) to recall the first explicit computation and b) to remind the introduction of the “ergosphere” which is the region between the horizon of a Kerr-Newmann metric and the surface of an infinite redshift where the energy extraction process can occur, and finally c) to emphasize how contrived, difficult and conceptually novel such a mechanism of energy extraction can be. It is a phenomenon which is not localized at a point but can occur in an entire region: a global effect which relies essentially on the concept of a field. However, it can only

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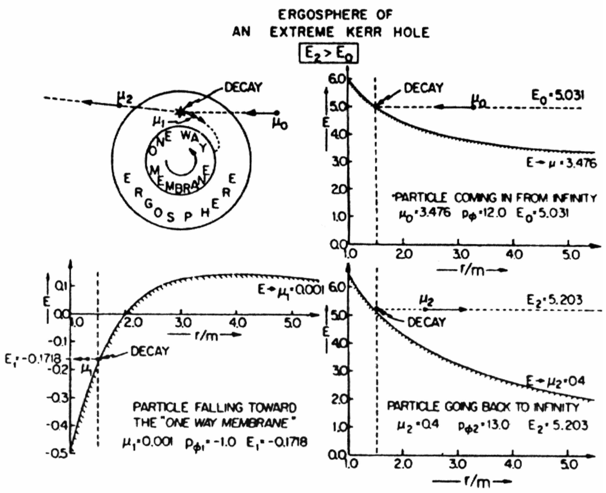

Figure 3. Decay of a particle of rest-plus-kinetic energy $E_\circ$ into a particle which is captured by the black hole with positive energy as judged locally, but negative energy E_1 as judged from infinity, together with a particle of rest-plus-kinetic energy $E_2 > E_\circ$ which escapes to infinity. The cross-hatched curves give the effective potential (gravitational plus centrifugal) defined by the energy E for constant values of p_ϕ and μ (reproduced from Ref. [27] with the kind permission of Ruffini and Wheeler).

work for very special parameters, and is in general associated with a reduction of the rest mass of the particle involved in the process. While it is almost trivial to slow down the rotation of a black hole and to increase its horizon by accretion of counterrotating particles, it is extremely difficult to extract the rotational energy from a black hole by a slowing-down process, as also clearly pointed out by the example in Fig. 3.

The establishment of this analogy offered us the opportunity to appreciate once more the profound difference of seemingly similar effects in general relativity and classical field theories. In addition we had the first glimpse to the existence of totally new phenomena, such as the dragging of the inertial frames around a rotating black hole, and thus to an entire new field of theoretical physics implied by the field equations of general relativity. The deep discussions of these problems with Demetrios Christodoulou, who was my first graduate student at the time in Princeton at the age of 17, led us to the discovery of the existence of "reversible and irreversible transformations" in black holes physics.

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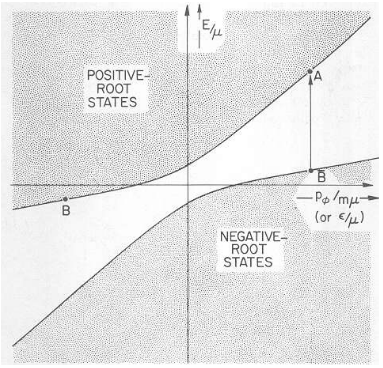

Figure 4. Reversing the effect of having added one particle A to the black hole by adding another particle B of the same rest mass but opposite angular momentum and charge in a "positive-root negative-energy state". The addition of B is equivalent to the subtraction of B^-. Thus the combined effect of the capture of particles A and B is an increase in the mass of the black hole given by the vector B^-A. This vector vanishes and reversibility is achieved when and only when the separation between positive root states and negative root states is zero, in this case the hyperbolas coalesce to a straight line (reproduced from Ref. [28]).

6 The First Analogy Between Thermodynamics and Black Hole Physics: Reversible and Irreversible Transformations

It was by analyzing the capture of test particles by an electromagnetic black hole that we identified a set of limiting transformations which did not affect the surface area. These special transformations had to be performed very slowly, with a limiting value of zero kinetic energy on the horizon of the EMBH (see Fig. 4). It then became immediately clear that the total energy of an EMBH could in principle be expressed as a sum of "rest energy", "Coulomb energy", and "rotational energy". The rest energy is "irreducible", the other two are variable by the process of adding and extracting energy, respectively.

While Wheeler was mainly addressing the issue of the thermodynamical analogy, I and Demetrios were interested in the fundamental issue of the energetics of EMBH using the tools of the reversible and irreversible transformations. We finally obtained the general mass-energy formula for black holes [28]:

$$E^2 = M^2c^4 = \left(M_{\mathrm{ir}}c^2 + \frac{Q^2}{2\rho_+}\right)^2 + \frac{L^2c^2}{\rho_+^2}, \tag{1}$$

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$$S = 4\pi\rho_+^2 = 4\pi\left(r_+^2 + \frac{L^2}{c^2M^2}\right) = 16\pi\left(\frac{G^2}{c^4}\right)M_{\rm ir}^2, \tag{2}$$

with the condition

$$\frac{1}{\rho_+^4}\left(\frac{G^2}{c^8}\right)\left(Q^4 + 4L^2c^2\right) \leq 1, \tag{3}$$

where $M_{\rm ir}$ is the irreducible mass, r_+ is the horizon radius, ρ_+ is the quasi-spheroidal cylindrical coordinate of the horizon evaluated at the equatorial plane, and S is the horizon surface area. Extreme black holes satisfy the equality in Eq. (3). The crucial point is that transformations at constant surface areas of the black hole, namely reversible transformations, can release an energy up to 29% of the mass-energy of an extremal rotating black hole and up to 50% of the mass-energy of an extremely magnetized and charged black hole. Since my Les Houches lectures *On the Energetics of Black Holes* [29], one of my main research goals has been to identify an astrophysical setting where the extractable mass-energy of the black hole could manifest itself. As we will see in the following, I propose that this extractable energy of an EMBH is the same as the energy source of gamma-ray bursts.

The thermodynamic analogy was further developed by Wheeler. By this time I had become convinced that the establishment of a one-to-one analogy between general relativistic effects and classical results was totally hopeless. It appeared to me that analogies could only be used as a very important tool to explore, possibly to be rationalized in a formula, the extremely vast theoretical world of the space-time structures contained in Einstein's theory of general relativity. A good example is our mass formula. Trying to enforce a perfect analogy is too risky and reductive.

7 Paradigm for Identifying the First "Black Hole" in Our Galaxy, and the Development of X-Ray Astronomy

The launch of the "Uhuru" satellite for the purpose of a first examination of the Universe in the X-ray spectrum, by a group directed by Riccardo Giacconi at the American Science and Engineering Department, marked a fundamental progress and generated a tremendous momentum in the field of relativistic astrophysics. The very fortunate work established simultaneous observations in the optical and in the radio wavelengths and thus allowed to have high-quality data on binary star systems composed of a normal star stripped off

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matter by a compact massive companion star: either a neutron star or a black hole.

The *Maximum Mass of a Neutron Star* was the subject of the thesis of Clifford Rhoades, my second graduate student at Princeton. A criteria was found there to overcome fundamental ignorance about the behaviour of matter at supranuclear densities by establishing an absolute upper limit to the neutron star mass. Our result was only based on general relativity, causality, and the behaviour of matter at nuclear and subnuclear densities. This work, presented at the 1972 Les Houches summer school, only appeared after a prolongued debate (see the reception and publication dates!) [30]. Its results were the following:

- the "black hole uniqueness theorem", implying the axial symmetry of the configuration and the absence of regular pulsations from black holes,
- the "effective potential technique", determining the efficiency of the energy emission in the accretion process, and
- the "upper limit on the maximum mass of a neutron star", discriminating between an unmagnetized neutron star and a black hole.

These three essential components established the paradigm for identifying the first black hole in Cygnus X1. The results were also presented in a widely attended session chaired by John Wheeler at the 1972 Texas Symposium in New York, extensively reported by the *New York Times.* The New York Academy of Sciences, which hosted the symposium, had just awarded me their prestigious Cressy Morrison Award for my work on neutron stars and black holes. Much to their dismay I never handed in the manuscript for the proceedings, since it coincided with a paper submitted for publication [31].

The definition of the paradigm did not come easily but matured slowly after innumerable discussions, mainly on the phone, both with Riccardo Giacconi and Herb Gursky. I still remember an irate professor of the Physics Department at Princeton pointing publicly to my outrageous phone bill of $274 for one month, at the time considered scandalous, due to my frequent calls to the Smithsonian, and a much more relaxed and sympathetic attitude about this situation by the department chairman Murph Goldberger. This work was finally summarized in two books: one with Herbert Gursky [32], following the 1973 AAAS Annual Meeting in San Francisco, and the second with Riccardo Giacconi [33] following the 1975 LXV Enrico Fermi Summer School (see also the proceedings of the 1973 Solvay Conference).

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8 More Analogies Between Thermodynamics and Black Hole Physics

The analogy between thermodynamics and general relativity became in 1971 the topic of the Ph.D. thesis of Wheeler's student Jacob Bekenstein. Through a profound set of gedanken experiments, Jacob pushed further the analogy between thermodynamics and black hole physics. Demetrios and I had formally established the existence of reversible transformations in black hole physics as well as the monotonic increase, as occurs for entropy in thermodynamics, of the irreducible mass $M_{\rm irr}$ of a black hole (from which the word "irreducible" arose). This was formally established independently by Steven Hawking in his area theorem [34]. The complete equivalence between the two results immediately follows from the identity relating the surface area $S = 16\pi M_{\rm irr}^2$ of the black hole to the irreducible mass $M_{\rm irr}$, as suggested by Bryce De Witt and confirmed in a quick calculation by Demetrios and myself. Jacob went one step further proposing that the area of the black hole S measured in Planck-Wheeler units could indeed be identified with the entropy [35]. He did this by formulating a statistical interpretation of the black hole entropy, and introducing the first generalized form of the first law of thermodynamics in physical processes involving black holes. Even today, thirty years later, these topics inspire lively debates. Jacob's proposal was extremely interesting and very intriguing at the time and remains so, for me, in some ways even today. It certainly was not contradictory, but I could not find a necessity for transforming it into an identity. The entire matter became the subject of even more intense discussions after Stephen Hawking proposed a physical process which, if true (in the sense used by Wigner), would transform all these theoretical conjectures into physical reality: the black hole quantum evaporation process [36]. Some three decades later, this topic also inspires lively debates. It is likely that these issues will be clarified once there is a theory encompassing both general relativity and relativistic quantum field theories. The basic properties of describing the Hawking radiation process from a black hole can simply be summarized in the following three formulae:

$$\begin{aligned}
\text{radiation temperature}: &\quad T \simeq 0.62\times 10^{-7}(M_\odot/M)\,\mathrm{K}\,, \\
\text{evaporation time}: &\quad \tau \simeq E/(dE/dt) \sim 2\times 10^{63}(M/M_\odot)^3\,\text{years}\,, \qquad (4)\\
\text{energy flux}: &\quad dE/dt \simeq 10^{-22}(M_\odot/M)^2\,\text{erg/sec}\,.
\end{aligned}$$

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9 Analogy Between the Electrodynamics of Black Hole and Perfect Conducting Sphere

Before closing this set of analogies I would like to recall a gedanken experiment Richard Hanni and I made by integrating the general relativistic equations back in 1974. The idea was to compute and draw the lines of force of a test charge in the field of a Schwarzschild black hole. This was the topic of the senior thesis of Rick, then my undergraduate student at Princeton. In order to solve this problem we decided to introduce the concept of an "induced charge" on a black hole [37]. By doing so, we proposed the analogy between a black hole and a classical system with a surface equal to the horizon and endowed with an appropriate conductivity (see Figs. 5 and 6). This gedanken experiment opened the way to the field of black hole electrodynamics which was further expanded in important contributions by Damour, Hanni, Ruffini, and Wilson [38] and references therein, and by Thibault Damour. Thibault came to Princeton in 1974 to work with me on his state doctorate thesis to be defended in Paris at the École Normale Supérieure. This beautiful thesis incorporated a detailed discussion of the general relativistic effects of electrodynamics of EMBH, including generalized Ohm's, Joule's, Ampere's, Navier Stoke's laws using as a tool the above-mentioned analogy. Interestingly, this analogy was taken very seriously and written up in the book by Kip Thorne and collaborators [39] as a final theory of black holes (see, however, the subtle relativistic effects and the different conclusions reached by Brian Punsly in his recent interesting book [40]).

The analogy was reconsidered in a widely publicized article on a full page in the science section of the *Frankfurter Allgemeine Zeitung* of January 31, 2001, shown to me by Hagen Kleinert one day after its appearance, praising "new results" in an article by Wilczek and a collaborator [41]. In that paper, Wilczek, without giving any reference, purports to extend our results with Hanni on the induced charge on a Schwarzschild black hole to the case of a Reissner-Nordström geometry with charge Q. They obtained the simple result for the effective potential

$$V(r) = q\left(\frac{Q-q}{r} - \frac{qR}{r^2 - R^2}\right) , \tag{5}$$

derived from the technique of introducing the image charge q. Unfortunately, they overlooked that in a very interesting set of papers, Bičák and his students Dvořák [42] and Ledvinka [43] had proven a totally new situation in the lines

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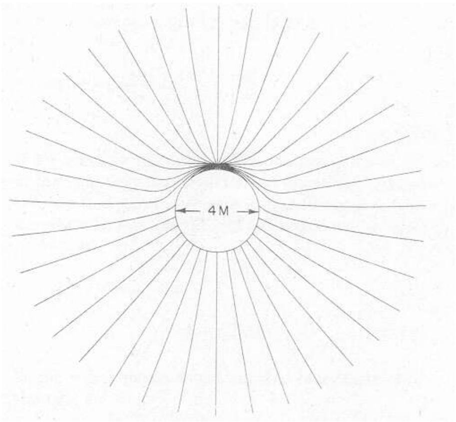

Figure 5. Lines of force of a charge near a black hole (reproduced from Ref. [37]).

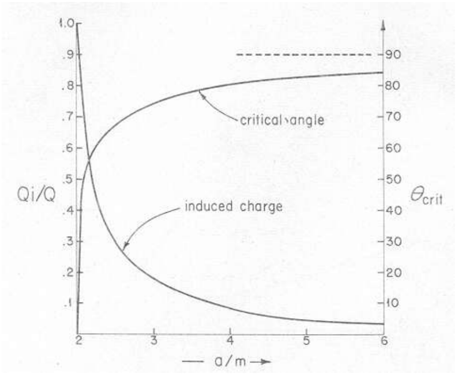

Figure 6. Induced charge on a Schwarzschild black hole (reproduced from Ref. [37]).

of force of a charge in the presence of a Reissner-Nordström geometry (see Fig. 7). In other words, in the limit $Q/M = 1$ of an extreme black hole, no line of force from the test particle crosses the horizon. We are confronted with a totally new effect for the electric field due to general relativity reminiscent of the Meissner effect in classical magnetic fields in the presence of superconductors. Such a general relativistic electric Meissner effect (GREME) does not appear to be contemplated in the Wilczek solution developed in analogy

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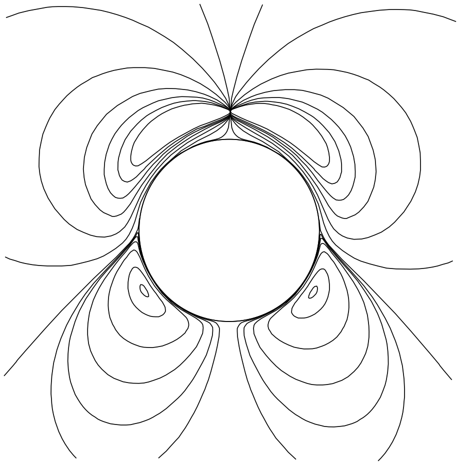

Figure 7. Lines of force of a point charge near an extreme EMBH with $Q = M$ (reproduced from Refs. [42,43]).

to my solution with Hanni. This case can be considered a propedeutic example of the incomparable richness of physical regimes present in the general relativity which, once again, transcends the direct analogies with classical field theories.

This series of events offer a clear pedagogical example of how the enforcement of direct and unproven analogies in general relativity can be dangerous and lead to incorrect conclusions.

10 Discovery of Gamma-Ray Bursts

In 1975 Herbert Gursky and myself had been invited by the AAAS to organize a session on neutron stars, black holes, and binary X-ray sources for the annual meeting in San Francisco. During the preparation of the meeting, we heard that some observations, made from the military Vela satellites and conceived in order to monitor the Limited Test Ban Treaty of 1963 on atomic bomb explosions, had just been unclassified. We asked Ian B. Strong to report, for the first time in a public meeting, on the observation of the gamma-ray bursts [32] (see Fig. 8). From the start it was clear that these signals were not coming either from the earth nor the planetary system. By 1991, a great improvement on the distribution of the gamma-ray bursts came with the

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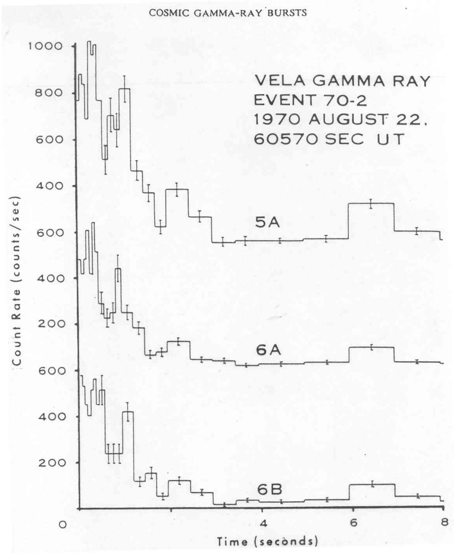

Figure 8. One of the first gamma-ray bursts observed by the Vela satellite (reproduced from an article of Strong in the book [32]).

NASA launch of the Compton Gamma-Ray Observatory which, in ten years of observation, gave a beautiful evidence for the perfect isotropy of the angular distribution of the gamma-ray burst sources in the sky (see Fig. 9). The sources had to be either at cosmological distances or very close to the solar system because one cannot detect the galactic anisotropical distribution there. In the meantime, the number of theories grew exponentially but without any clear conclusion. Quite prominent among these theories were some relating the gamma-ray burst phenomenon to the Hawking radiation process.

11 Analogy of Heisenberg-Euler Critical Capacitor and Vacuum Polarization Around Macroscopic Black Hole

In 1975, following the work of Christodoulou and Ruffini on the energetics of black holes [28], we pointed out [44] the relevance of the vacuum polarization process à la Heisenberg-Euler-Schwinger [45,46] around EMBHs. Such a process can only occur for EMBHs of mass smaller then $7.2 \times 10^6 M_\odot$. The basic energetics implications were contained in Table 1 of that paper [44], where it

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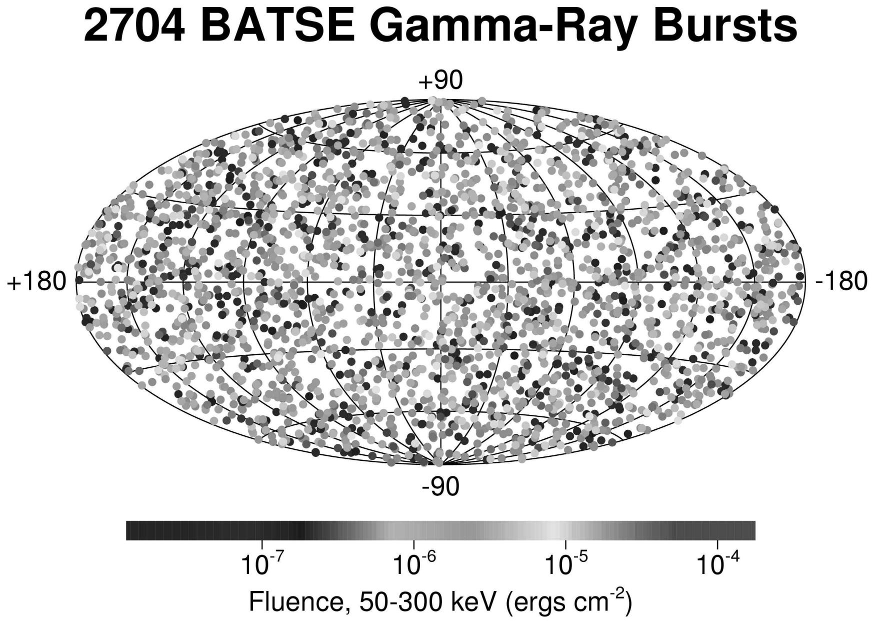

Figure 9. Angular distribution of gamma-ray bursts in galactic coordinates from the Compton GRO satellite.

was also shown that this process is almost reversible in the sense explained by Christodoulou and Ruffini [28], and that it extracts the mass energy of an EMBH very efficiently. We also pointed out that this vacuum polarization process around an EMBH offered a natural mechanism for explaining gamma-ray bursts, in particular their large characteristic energy of 10^{54} ergs (see Fig. 10).

12 Beppo-SAX Satellite and Instantaneous Destruction of More Than 135 Theoretical Models

It was only with the very unexpected and fortuitous observations of the Beppo-SAX satellite that the existence of a long-lasting afterglow of these sources was identified. This led to determining a much more accurate position for these sources in the sky, which permitted for the first time their optical and radio identification. The optical identification has led to the de-

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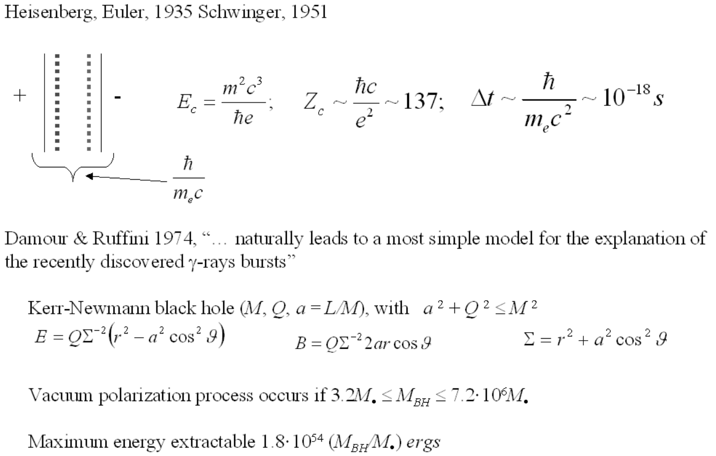

Heisenberg, Euler, 1935 Schwinger, 1951

$$E_c = \frac{m^2 c^3}{\hbar e}; \quad Z_c \sim \frac{\hbar c}{e^2} \sim 137; \quad \Delta t \sim \frac{\hbar}{m_e c^2} \sim 10^{-18} s$$

Damour & Ruffini 1974, "… naturally leads to a most simple model for the explanation of the recently discovered γ-rays bursts"

Kerr-Newmann black hole (M, Q, $a = L/M$), with $a^2 + Q^2 \leq M^2$

$$E = Q\Sigma^{-2}\left(r^2 - a^2 \cos^2 \vartheta\right) \qquad B = Q\Sigma^{-2} 2ar \cos \vartheta \qquad \Sigma = r^2 + a^2 \cos^2 \vartheta$$

Vacuum polarization process occurs if $3.2 M_\bullet \leq M_{BH} \leq 7.2 \cdot 10^6 M_\bullet$

Maximum energy extractable $1.8 \cdot 10^{54}$ ($M_{BH}/M_\bullet$) *ergs*

Figure 10. Summary of the EMBH vacuum polarization process (see Ref. [44] for details).

termination of their cosmological distances and to their paramount energetic requirements, in some cases $\geq 10^{54}$ ergs (see Ref. [47]).

The very fortunate interaction and resonance between X-ray, optical, and radio astronomy which, in the seventies, allowed the maturing of the physics and astrophysics of neutron stars and black holes (see e.g. Ref. [33]), promises to be active again in these days in unravelling the physics and astrophysics of the gamma-ray burst sources.

The observations of the Beppo-SAX satellite had a sobering effect on the theoretical development on gamma-ray burst models. Practically all existing theories (see a partial list in Fig. 11) were at once wiped out, not being able to fit the stringent energy requirements imposed by observations. They were particularly constraining for the models based on the Hawking radiation process (see Table 1 for details). These are by far the theoretical predictions furthest from any observational data in the entire history of the homo sapiens and possibly in the entire Universe.

13 Analogy Between Ergosphere and Dyadosphere of Black Holes

The enormous energy requirements of gamma-ray bursts, which are very similar to those predicted by Damour and Ruffini in 1975 [44], have convinced us to return to our earlier work in studying more accurately the process of vac-

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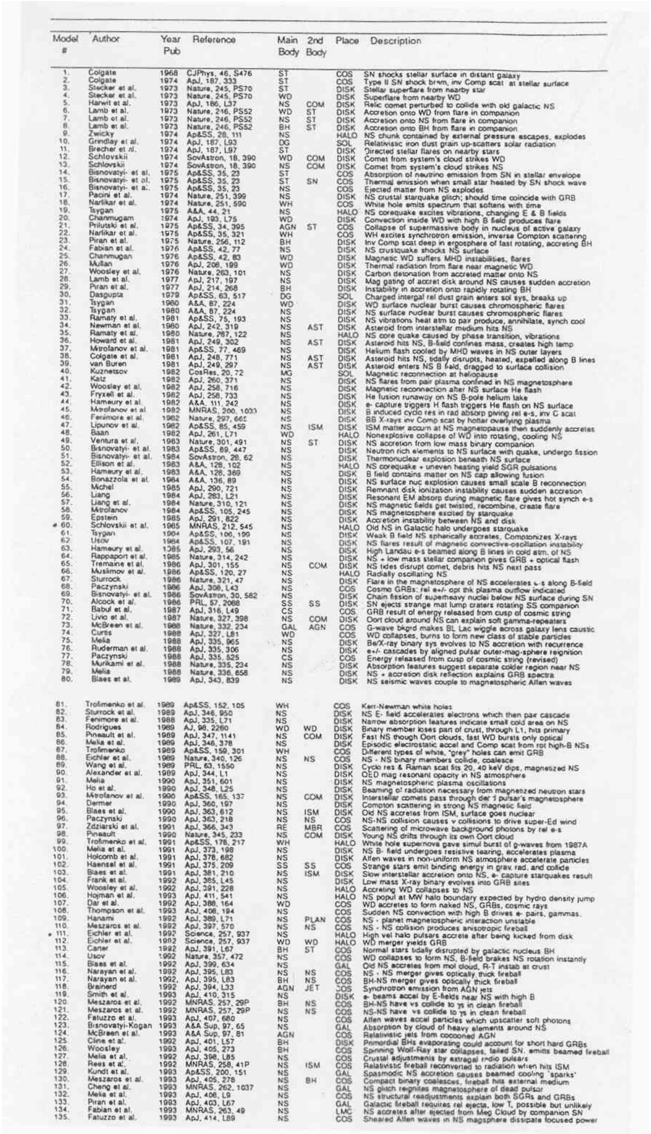

Model #	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 216, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap&SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flares on nearby stars
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap&SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap&SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap&SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugan	1976	Ap&SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag gating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap&SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap&SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap&SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al.	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap&SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap&SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot synch e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap&SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
* 60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap&SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap&SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm. of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap&SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e+/- opt thk plasma outflow indicated
69.	Bisnovatyi- et al.	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
72.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
73.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
74.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
75.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion with recurrence
76.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+/- cascades by aligned pulsar outer-mag-sphere reignition
77.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
78.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
79.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
80.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
81.	Trofimenko et al.	1989	Ap&SS, 152, 105	WH		COS	Kerr-Newman white holes
82.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E- field accelerates electrons which then pair cascade
83.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
84.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
85.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS though Oort clouds, fast WD bursts only optical
86.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NSs
87.	Trofimenko	1989	Ap&SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRB
88.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
89.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
90.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
91.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
92.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
93.	Mitrofanov et al.	1990	Ap&SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
94.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
95.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
96.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes ν collisions to drive super-Ed wind
97.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
98.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
99.	Trofimenko et al.	1991	Ap&SS, 178, 217	WH		HALO	White hole supernova gave simul burst of g-waves from 1987A
100.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B- field undergoes resistive tearing, accelerates plasma
101.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
102.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav. rad. and collide
103.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
104.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolves into GRB sites
105.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapses to NS
106.	Hojman et al.	1993	ApJ, 411, 541	NS		HALO	NS popul at MW halo boundary expected by hydro density jump
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRBs, cosmic rays
108.	Thompson et al.	1993	ApJ, 408, 194	NS		COS	Sudden NS convection with high B drives e- pairs, gammas.
109.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
110.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
* 111.	Eichler et al.	1992	Science, 257, 937	NS		HALO	High vel halo pulsars accrete after being kicked from disk
112.	Eichler et al.	1992	Science, 257, 937	WD	WD	HALO	WD merger yields GRB
113.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
114.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
115.	Blaes et al.	1992	ApJ, 399, 634	NS		GAL	Old NS accretes from mol cloud, R-T instab at crust
116.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
117.	Narayan et al.	1992,	ApJ, 395, L83	BH	NS	COS	BH-NS merger gives optically thick fireball
118.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
119.	Smith et al.	1993	ApJ, 410, 315	NS		DISK	e- beams accel by E-fields near NS with high B
120.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have νs collide to γs in clean fireball
121.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have νs collide to γs in clean fireball
122.	Fatuzzo et al.	1993	ApJ, 407, 680	NS		COS	Alfen waves accel particles which upscatter soft photons
123.	Bisnovatyi-Kogan	1993	A&A Sup, 97, 65	NS		GAL	Absorption by cloud of heavy elements around NS
124.	McBreen et al.	1993	A&A Sup, 97, 81	AGN		COS	Relativistic jets from cocooned AGN
125.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
126.	Woosley	1993	ApJ, 405, 273	BH		COS	Spinning Wolf-Rayet star collapses, failed SN, emits beamed fireball
127.	Melia et al.	1992	ApJ, 398, L85	NS		COS	Crustal adjustments by extragal radio pulsars
128.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM
129.	Kundt et al.	1993	Ap&SS, 200, 151	NS		GAL	Spasmodic NS accretion causes beamed cooling "sparks"
130.	Meszaros et al.	1993	ApJ, 405, 278	NS	BH	COS	Compact binary coalesces, fireball hits external medium
131.	Cheng et al.	1993	MNRAS, 262, 1037	NS		GAL	NS glitch reignites magnetosphere of dead pulsar
132.	Melia et al.	1993	ApJ, 408, L9	NS		COS	NS structural readjustments explain both SGRs and GRBs
133.	Piran et al.	1993	ApJ, 403, L67	NS		GAL	Galactic fireball requires rel ejecta, low T, possible but unlikely
134.	Fabian et al.	1993	MNRAS, 263, 49	NS		LMC	NS accretes after ejected from Meg Cloud by companion SN
135.	Fatuzzo et al.	1993	ApJ, 414, L89	NS		COS	Sheared Alfen waves in NS magsphere dissipate focused power

Figure 11. Partial list of theories before the Beppo-SAX, from a talk presented at MGIXMM [48].

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Table 1. Hawking radiation process versus gamma-ray burst observations. The comparison is performed for a) the energetics $E_{\rm tot} \simeq 10 M_\odot \simeq 10^{55}$erg, b) the time scale $\tau \simeq 1$ sec, and c) the spectrum energy $T = 10^8$K.

a)

theoretical value	observed value	discrepancy
$T = 6.2 \times 10^{-9}$K	$T \simeq 10^8$K	$\sim 10^{-17}$
$\tau = 10^{73}$sec	$\tau \simeq 1$sec	$\sim 10^{73}$
$\left(\frac{dE}{dt}\right) = 10^{-24}$ erg/sec	$\left(\frac{dE}{dt}\right) \simeq 10^{54}$ erg/sec	$\sim 10^{-78}$

b)

theoretical value	observed value	discrepancy
$E_{\rm tot} \simeq 10^{-24} M_\odot \simeq 10^{30}$erg	$E_{\rm tot} \simeq 10^{55}$erg	$\sim 10^{-25}$
$T = 10^{17}$K	$T \simeq 10^8$K	$\sim 10^9$
$\left(\frac{dE}{dt}\right) = 10^{26}$ erg/sec	$\left(\frac{dE}{dt}\right) \simeq 10^{54}$ erg/sec	$\sim 10^{-28}$

c)

theoretical value	observed value	discrepancy
$E_{\rm tot} \simeq 10^{-9} M_\odot \simeq 10^{45}$erg	$E_{\rm tot} \simeq 10^{55}$erg	$\sim 10^{-10}$
$\tau = 10^{43}$sec	$\tau \simeq 1$sec	$\sim 10^{43}$
$\left(\frac{dE}{dt}\right) = 10^{-4}$ erg/sec	$\left(\frac{dE}{dt}\right) \simeq 10^{54}$ erg/sec	$\sim 10^{-58}$

uum polarization and the region of pair creation around an EMBH. This has led a) to the new concept of the dyadosphere of an EMBH ("dyado" from the Greek word for "pair"), b) to the concept of a plasma-electromagnetic (PEM) pulse, and c) to the analysis of its temporal evolution generating signals with the characteristic features of a gamma-ray burst.

In our theoretical approach, we claim that, by the observations of gamma-ray bursts, we are witnessing the formation of an EMBH, and that we thus follow the process of a gravitational collapse in real time. Even more important: the tremendous energies involved in the energetics of these processes

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coincide with the extractable energy of black holes which is described by the Eqs. (1)–(3).

Various models have been proposed in order to extract the rotational energy of black holes by processes of relativistic magnetohydrodynamics (see e.g. Ref. [49]). It should be expected, however, that these processes are relevant over the long time scales characteristic of accretion processes.

In the present case of gamma-ray bursts, a sudden mechanism appears to be at work on time scales of the order of few seconds or shorter, and they are naturally explained by the vacuum polarization process introduced by Damour and Ruffini [44].

The fundamental new points we have found reexamining our previous work can be summarized as follows (see Ref. [50] for details):

- The vacuum polarization process can occur in an extended region around the black hole called the dyadosphere, extending from the horizon radius r_+ out to the dyadosphere radius $r_{\rm ds}$. Only black holes with a mass larger than the upper limit of a neutron star and up to a maximum mass of $7.2 \times 10^6 M_\odot$ can have a dyadosphere.
- The efficiency of transforming the mass-energy of a black hole into particle-antiparticle pairs outside the horizon can approach 100% for black holes in the above mass range.
- The pairs created are mainly positron-electron pairs and their number is much larger than the quantity Q/e one would have naively expected on the grounds of qualitative considerations. It is actually given by $N_{\rm pairs} \sim Q/e \times r_{ds}/(\hbar/mc)$, where m and e are the electron mass and charge, respectively. The energy of the pairs, and consequently the emission of the associated electromagnetic radiation, peaks in the gamma-X-ray region, as a function of the black hole mass.

Let us now recall the main results on the dyadosphere obtained by Preparata, Ruffini, and Xue [50]. Although the general considerations presented by Damour and Ruffini [44] did refer to a Kerr-Newmann field with axial symmetry around the rotation axis, we have there considered, for simplicity, the case of a non-rotating Reissner-Nordström EMBH to illustrate the basic gravitational-electrodynamical process. The dyadosphere then lies between the radius

$$r_{\rm ds} = \left(\frac{\hbar}{mc}\right)^{\frac{1}{2}} \left(\frac{GM}{c^2}\right)^{\frac{1}{2}} \left(\frac{m_{\rm p}}{m}\right)^{\frac{1}{2}} \left(\frac{e}{q_{\rm p}}\right)^{\frac{1}{2}} \left(\frac{Q}{\sqrt{G}M}\right)^{\frac{1}{2}} \tag{6}$$

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and the horizon radius

$$r_+ = \frac{GM}{c^2}\left(1+\sqrt{1-\frac{Q^2}{GM^2}}\right) . \tag{7}$$

The number density of pairs created in the dyadosphere is

$$N_{e^+e^-} \simeq \frac{Q-Q_c}{e}\left[1+\frac{(r_{ds}-r_+)}{\hbar/mc}\right] , \tag{8}$$

where $Q_c = 4\pi r_+^2 m^2 c^3/\hbar e$. The total energy of pairs converted from the static electric energy and deposited within the dyadosphere is then

$$E^{\rm tot}_{e^+e^-} = \frac{1}{2}\frac{Q^2}{r_+}\left(1-\frac{r_+}{r_{\rm ds}}\right)\left[1-\left(\frac{r_+}{r_{\rm ds}}\right)^2\right] . \tag{9}$$

There are many interesting analogies between the ergosphere and the dyadosphere:

- Both of them are extended regions around the black hole.
- In both regions the energy of the black hole can be extracted, approaching the limiting case of reversibility from Christodoulou and Ruffini [28].
- The electromagnetic energy extraction by the pair creation process in the dyadosphere is much simpler and less contrived than the corresponding process of extracting rotational energy from the ergosphere.

14 Analogies Between EM Pulse of Atomic Explosion and PEM Pulse of Black Holes

The analysis of the radially resolved evolution of the energy deposited within the e^+e^--pair and photon-plasma fluid created in the dyadosphere of an EMBH is much more complex then we had initially anticipated. In this respect, the collaboration with Jim Wilson and his group at Livermore Radiation Laboratory was very important for us. Recently, we decided to join forces in a new collaboration, renewing our previous successful collaboration of 1974 [49]. We proceeded in parallel: in Rome with simple, almost analytic models, in Livermore by confirming these models with computer codes [51,52].

For the evolution we assumed the relativistic hydrodynamic equations (for details see Refs. [53,54]). We assumed the plasma fluid of e^+e^--pairs,

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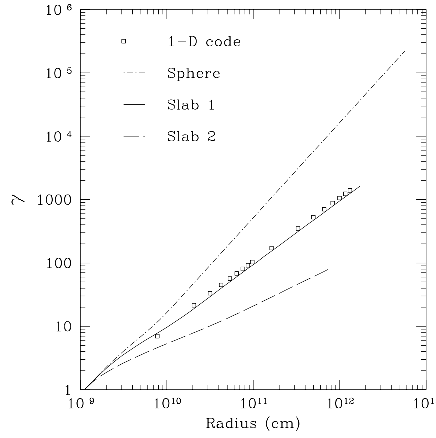

Figure 12. Lorentz factor γ as a function of radius. Three models for the expansion pattern of the e^+e^- pair plasma are compared with the results of the one-dimensional hydrodynamic code for a $1000M_\odot$ black hole with charge $Q = 0.1Q_{\max}$. The 1-D code has an expansion pattern that strongly resembles that of a shell with constant coordinate thickness (reproduced from Ref. [54]).

photons and baryons to be a simple perfect fluid in curved space-time. The baryon-number and energy-momentum conservation laws are

$$(n_B U^\mu)_{;\mu} = (n_B U^t)_{,t} + \frac{1}{r^2}(r^2 n_B U^r)_{,r} = 0 \ , \tag{10}$$

$$(T_\mu^\sigma)_{;\sigma} = 0, \tag{11}$$

with the rate equation

$$(n_{e^\pm} U^\mu)_{;\mu} = \overline{\sigma v}\left[n_{e^-}(T) n_{e^+}(T) - n_{e^-} n_{e^+}\right] \ , \tag{12}$$

where U^μ is the four-velocity of the plasma fluid, n_B is the proper baryon-number density, $n_{e^\pm}$ are the proper densities of electrons and positrons $e^\pm$, σ is the mean pair annihilation-creation cross-section, v is the thermal velocity of $e^\pm$, and $n_{e^\pm}(T)$ are the proper number-densities of $e^\pm$ at an appropriate equilibrium temperature T. The calculations are continued until the plasma fluid expands, cools, and the e^+e^- pairs recombine, making the system optically thin.

The results of the Livermore computer work are compared and contrasted with three almost analytical models:

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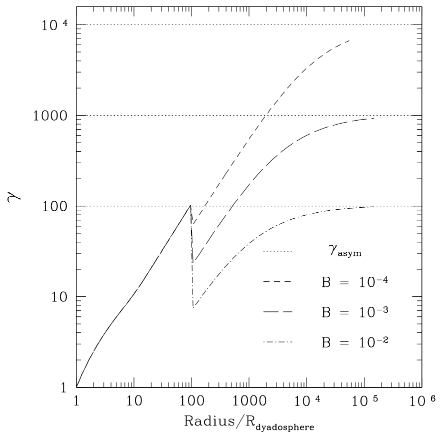

Figure 13. Lorentz factor γ as a function of radius for the PEM pulse interacting with the baryonic matter of the remnant (PEMB pulse) for selected values of the baryonic matter (reproduced from Ref. [55]).

- spherical model where the radial component of four-velocity is of the form $U(r) = Ur/\mathcal{R}$ with U being the four-velocity at the surface $\mathcal{R}$ of the plasma, similar to a portion of a Friedmann model,
- slab 1 where $U(r) = U_r = \text{const.}$, which is an expanding slab with constant width $\mathcal{D} = R_\circ$ in the coordinate frame in which the plasma is moving,
- slab 2 which is an expanding slab with constant width $R_2 - R_1 = R_\circ$ in the comoving frame of the plasma.

We compute the relativistic Lorentz factor γ of the expanding e^+e^- pair and photon plasma. In Fig. 12 we see a comparison of the Lorentz factor of the expanding fluid as a function of radius for all these models. We can see that the one-dimensional computation, of which only a few significant points are plotted, matches the expansion pattern of a shell of constant coordinate thickness.

In analogy with the notorious electromagnetic radiation EM pulse of some explosive events, we called this relativistic counterpart of an expanding pair electromagnetic radiation shell a PEM pulse. In recent works we have computed the interaction of the expanding plasma with the surrounding baryonic matter [55] (see Fig. 13). We have also been able to follow the expansion

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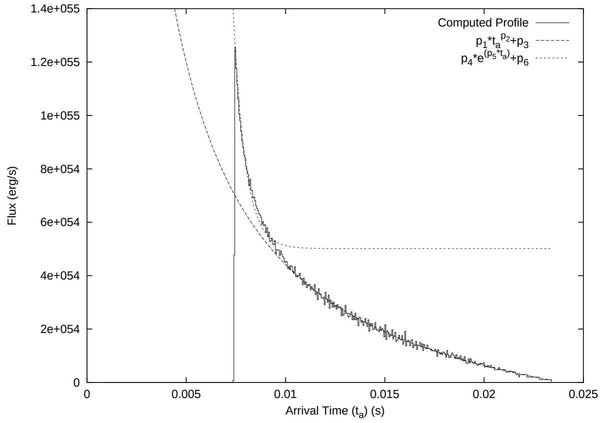

Figure 14. Proper gamma-ray burst from an EMBH with $M = 100M_\odot$ and $Q = 0.1Q_{\max}$ (reproduced from Ref. [56]).

process all the way to the point where the transparency condition is reached and what we have defined the "proper gamma-ray burst" is emitted [56] (see Fig. 14). These results of our theoretical model have reached the point where they can be subjected to a direct comparison with observational data.

15 Three New Paradigms for Interpreting Gamma-RAY Bursts

Starting from this theoretical background, we have moved ahead to fit, for the first time, the observational data on the ground of the EMBH model. We have used, as a prototype, the object GRB 991216, both for its very high energetics, which we have estimated in the range of $E_{\rm dya} \sim 9.57 \times 10^{52}$ ergs, and for the superb data obtained by the Chandra and RXTE satellites. We have found a necessity to formulate in our novel approach three new paradigms, in order to understand the gamma-ray burst phenomenon:

- the relative space-time transformations (RSTT) paradigm (see Ref. [57]),
- the interpretation of the burst structure (IBS) paradigm (see Ref. [58]),
- the multiple-collapse time sequence (MCTS) paradigm (see Ref. [59]).

These results are currently under refereeing process in *Astrophysical Journal Letters* since 28/11/2000.

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16 Conclusions

From the above experience, I can venture to formulate some conclusions, which may be of general validity.

16.1 On Analogies

- Analogies have been extremely helpful in establishing similarities and deepening our physical understanding, if applied to two circumstances both derived within a general relativistic framework. The analogies between dyadosphere and ergosphere are good examples.
- Analogies between classical regimes and general relativistic regimes have sometimes been helpful in giving a glance at the enormous richness of new physical processes contained in Einstein's theory of space-time structure. In some cases they have allowed us to reach new knowledge and formalize new physical laws, the derivation of Eqs. (1)–(3) being a good example. Such analogies have also dramatically evidenced the enormous differences in depth and physical complexity between classical physics and general relativistic effects. The extraction of rotational energy from a neutron star and a rotating black hole are good examples.
- In no way an analogy based on classical physics can be enforced for general relativistic regimes. Such an analogy is too constraining, and the relativistic theory shows systematically a wealth of novel physical circumstances and conceptual subtleties which are unreachable within a classical theory. The analogies in classical electrodynamics we just outlined are good examples.

16.2 On New Paradigms

The establishment of new paradigms is essential to the scientific process, and certainly not easy to obtain. Such paradigms are important in order to guide a meaningful comparison between theories and observations, and much attention should be given to their development and inner conceptual consistency.

16.3 On Observational Data

The major factors in driving the progress of scientific knowledge are always the confrontation of theoretical predictions with observational data. In recent

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years, the evolution of new technologies has allowed to dramatically improve the sensitivity of observational apparata. It is gratifying that in this process of learning the structure of our Universe, observational data do not intervene in a marginal way, but with clear and unequivocal results: they confirm by impressive agreement the correct theories and disprove, by equally impressive disagreement, the wrong ones. Our examples are also significant features of this process.

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