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Memorie della

Hunting for Sub-Millisecond Pulsars

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Abstract. In this paper I retrace some particularly significant moments of my scientific collaboration with the late friend and colleague Nichi D'Amico. The projects mentioned well highlight the extraordinary variety of his interests in avant-garde astrophysical problems and, more generally, in leading themes in fundamental physics. Indeed, they testify to his relationship with scientific investigation, always careful to value experimental feedback as an essential guide for theoretical speculations. From this context emerges the conviction, which we have always shared with Nichi, that astrophysical phenomena today offer the best laboratory in which to verify our most extraordinary and daring theories on the structure of the physical world.

Key words. Neutron Stars: pulsars – Equation of State of Ultra-dense Matter – Quantum Gravity

1. Introduction: a charismatic young scientist

I started working with Nichi in 1996, when I was employed as a Post Doc at the Astronomy Group of the University of Leicester, headed by Andrew King.

I had met Nichi almost fifteen years earlier, when I was attending the second course in experimental physics (*Esperimentazioni di Fisica II*) at the University of Palermo. I remember him, young assistant of that course, giving us programming lessons in the military uniform of an airman. In fact, he attended the Recruit Training Course in Trapani. I perfectly remember the overflowing and contagious enthusiasm of that improbable young-scientist-in-uniform for scientific research *tout court*, and for astronomy in particular. I have clear in my mind the sharp gaze with which he illustrated to me, in a captivating way, the different methodologies to generate pseudo-random data that obeyed a specific statistical distribution, using simple random numbers generators between zero and one: more practical and easy to understand methods, such as that of sampling the area subtended by the distribution with points randomly distributed on a rectangle that enveloped most of the function, more sophisticated and fascinating methods such as that of inversion to generate a Poissonian sequence of events with uniform probability of occurrence over time: my first uncertain steps in the fascinating world of Monte Carlo simulations. Thirty years later, those fascinating discussions on the randomness and uniformity of the cumulative distribution would have helped me in my research on the quantum structure of Space-Time.

Nichi was able to induce, in the interested interlocutor, an extraordinary curiosity towards all natural phenomena, even if apparently simple, capable of soliciting profound reflections which, in recent times, would have stimulated the common interest in the design of experiments specifically dedicated to experimental verification of the consequences of some theories of Quantum Gravity that predict a temporal and spatial granularity (first order) at the Planck scale ($t_{\rm min} \sim t_{\rm Planck} = \sqrt{G\hbar/c^5} \sim 10^{-43}$ seconds and $\ell_{\rm min} \sim \ell_{\rm Planck} = \sqrt{G\hbar/c^3} \sim 10^{-33}$ centimetres, respectively), the visionary project *GrailQuest* (Gamma Ray Astronomy International Laboratory for QUantum Exploration of Space Time), which Nichi supported with interest.

2. Sub-millisecond pulsars: the quest for the Strange Quark Matter

But, going by order and going back to the end of the last century, I remember very well the fervour of his words when he illustrated to me the extraordinary discoveries that, as a member of the Parkes Pulsar Team, had made with his Australian, British, American, Canadian colleagues: Millisecond Radio Pulsars sprouted galore in the heart of Globular Clusters scrutinised with the huge eye of the Australian radio telescope, greedy prey for that handful of intrepid, eager, hunters of the wonders of the cosmos.

Neutron Stars, spinning at about a thousand times per second, reaching nearly the speed of light at the equator, unimaginably compact objects (a star concentrated in a sphere of ten kilometres radius) fascinated us for the striking contrast between properties so extreme and an almost inconceivable structural simplicity in an astronomical object: the immense force of gravity capable of eliminating almost any secondary structure in an attempt to subject the multiform variety of matter to the astounding spherical symmetry that the very nature of this force imposes.

I perfectly remember the intuition, shared by both of us, of using the global properties of these marvelous, very dense spheres, subjected to vertiginous rotations, to investigate their elusive and otherwise inaccessible internal structure, to carry out, in short, experiments on matter subjected to extreme conditions, in order to reveal its intimate structure, the search for the Holy Grail of Nuclear Physics: the Equation of State of ultra-dense matter. Are Neutron Stars composed by a crystalline crust surrounding a superfluid ocean of neutrons (gravitationally-bound neutron star, see Burderi & D'Amico (1997) for a detailed discussion of gravitationally-bound *vs.* self-bound neutron stars), or, as theorised by some daring theoretical physicists, do they harbour a nucleus of the more stable and compact state of matter (self-bound neutron star), a uniform mixture of up, down and strange quarks, the so-called Strange Quark Matter?

We therefore started studying different types of mechanical deformations induced by the rapid rotation on these precious geoids, guardians of the last secrets of the cosmos. As shown in figure 1, from the paper by Burderi & D'Amico (1997), the maximum allowed spin frequency for a gravitationally bound neutron star depends on the Equation of State of ultra-dense matter adopted. And here comes the conclusions, extraordinarily simple and, therefore, enormously constraining in this respect. In line with the results proposed by other authors (*e.g.* Koranda et al. 1997 and Glendenning 1992), the discovery of a radio pulsar with a rotation period of less than one third of a millisecond would, *ipso facto*, prove the existence of the Strange Quark Matter, the most stable state of aggregation of matter!

Two points still remained to be clarified: to outline a plausible astrophysical scenario spinning a Neutron Star up to these dizzying rotations and to design an experiment with selected characteristics to identify this possible type of pulsar in very rapid rotation. I dedicated myself to conceive semi-detached binary systems, harbouring a Neutron Star, in which a prolonged phase of mass-transfer allowed the Neutron Star to accrete the angular momentum corresponding to the rotation below one millisecond, while Nichi, with the extraordinary technical-experimental competence that coexisted in him with the interest for the most delicate and profound theoretical problems, dedicated himself to conceiving a Survey with characteristics (*e.g.* temporal resolution, sampling frequency, frequency width of filters,

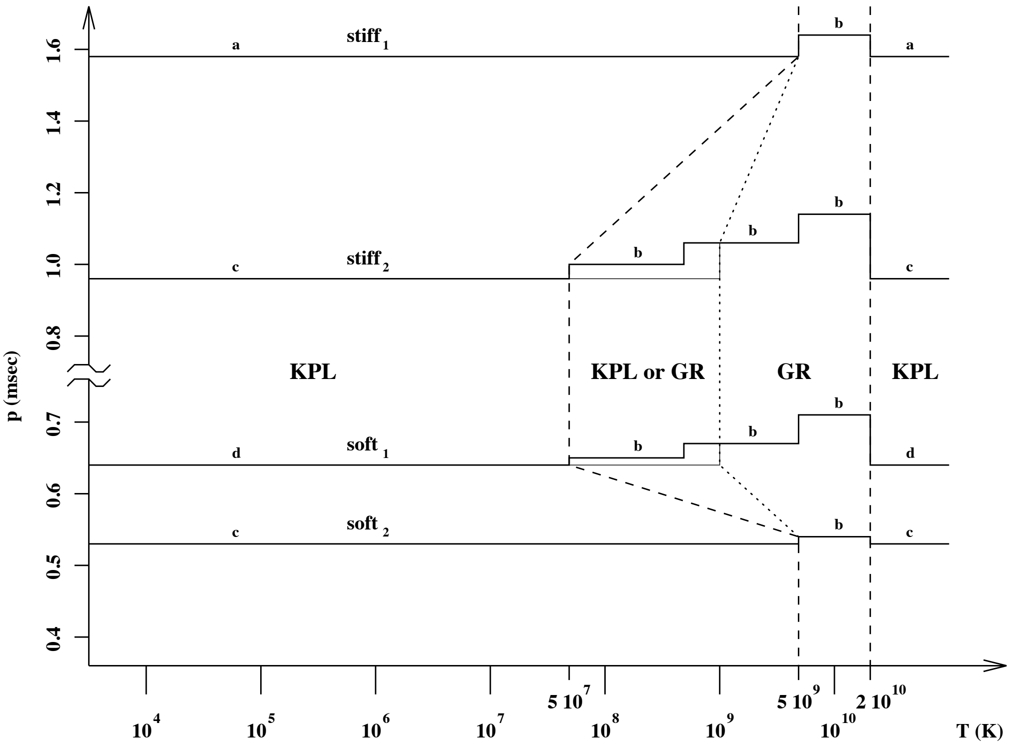

Fig. 1. Original figure from the paper by Burderi & D'Amico (1997). Schematic plot of the shortest possible periods for a rotating NS vs. the NS temperature. Curves labeled soft_1 and soft_2 refer to EOS B and baryon masses of $M_\mathrm{b} = 1.4\,M_\odot$ and $M_{\mathrm{b\,max}} = 1.63\,M_\odot$, respectively ; curves labeled stiff_1 and stiff_2 refer to EOS L and baryon masses of $M_\mathrm{b} = 1.4\,M_\odot$ and $M_{\mathrm{b\,max}} = 3.23\,M_\odot$, respectively. KPL indicates the zones, delimited by the first and the last dashed line, where the minimum period is determined by the centrifugal instabilities. GR indicates the zone where the minimum period is determined by the gravitational radiation–driven instability. In the zone between the left dashed line and the dotted line, KPL may be the limiting instability if mutual friction damps the GR instability. (a) From Friedman et al. (1986); (b) from Cutler & Lindblom (1987); (c) from Cook et al. (1994); (d) from Friedman & Ipser (1992).

bandwidth, etc.) designed to obtain sensitivity at very high frequencies at the price of a worsen sensitivity for the detection of slower Pulsars. In figure 2, originally published in D'Amico (2000), we show the sensitivity profile of the Bologna survey.

This work, which we published in Astrophysical Journal (Burderi & D'Amico 1997), greatly influenced, in the spirit and methodology described, my subsequent approach to the problems of theoretical astrophysics.

The constant attention to the possibility of an experimental confirmation of the proposed theories, and the belief, today shared by most, that astrophysics constitutes the last accessible laboratory to verify the theories on the profound nature of the physical world, are, in my opinion, the two great intuitions that Nichi always had in mind. This, in a nutshell, is, in my opinion, the extraordinary scientific legacy that he left us and that has profoundly influenced all his collaborators. This is the unifying leitmotif of his multifaceted activity as a highly talented scientist.

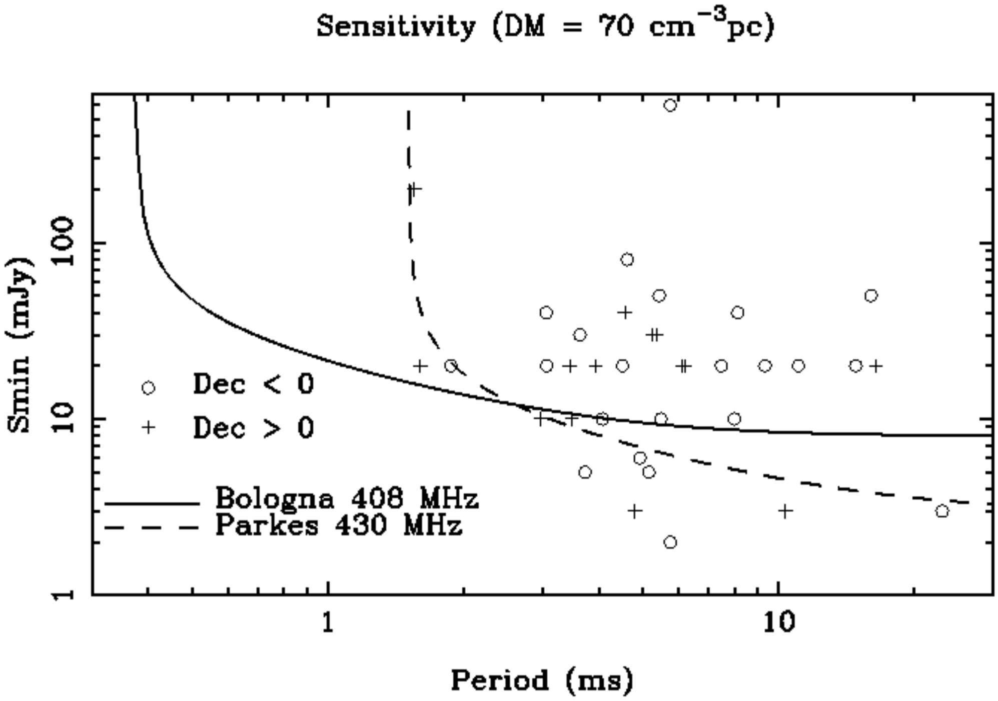

Fig. 2. Original figure from the paper by D'Amico (2000). Sensitivity profile of the Bologna survey compared with that of the low frequency Parkes survey (Manchester et al. 1996). The positions of the known millisecond pulsars in the Northern and Southern sky are indicated.

It is absolutely no coincidence that his name is linked to the discovery of the Double Pulsar (Burgay et al. 2003), the binary system of two Radio Pulsars that has allowed astronomers to verify with the maximum precision obtainable to date the predictions of General Relativity at a better level than one part over a thousand in many respects. I remember the fervent words with which Nichi described the intense emotions of those days: on holiday in the Alps, his wife Adriana waving her mobile phone looking for a weak telephone field in the thin air between farms and huts for a precarious connection to the network in order to prepare the latest version of the Nature paper that announced the discovery of the system? the irrepressible emotion that overwhelms the man of science when, in front of his astonished and satisfied eyes, Nature opens up its treasures. But the scientific companions of that beautiful journey will say, better than I could do, elsewhere, of this extraordinary adventure undertaken by Nichi in the fascinating and unexplored lands of leading scientific research.

3. Probing the innermost structure of Quantum Space-Time: a recent project at the University of Cagliari

Here I want to recall the mutual and profound esteem that characterised my relationship with Nichi. I am sure that, without any rhetoric, the recognition of the poignant passion for knowledge was the basis of our relationship, essential, in some ways, but indissolubly intense. I am absolutely certain that in this spirit he called me for a professorship at the University of Cagliari, where he was about to undertake a new challenge, the completion of the construction of the Sardinia Radio Telescope.

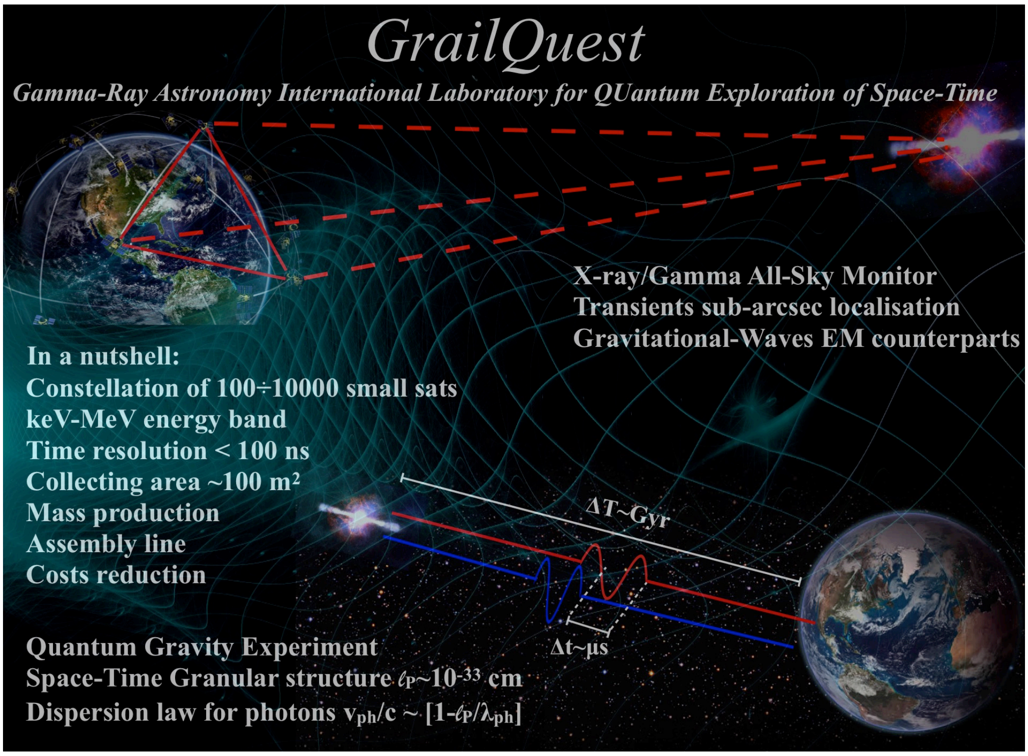

Fig. 3. Original figure from the paper by Burderi et al. (2020). The *GrailQuest* project.

And it is here in Cagliari that, together with Nichi and an international group of audacious scientists, we have conceived an experiment to probe the deepest structure of Space-Time in search of the extreme limits that many models of Quantum Gravity set for the stage of the cosmos. Indeed, many theoretical studies present a lower limit to the dizzying unlimited divisibility of space and time (see *e.g.* Burderi et al. 2016 and references therein). In this granular fabric, a light wave interacts with Space-Time grains, partially slowing down its frenetic rush when its wavelength approaches the Planck length, the distance between the successive *atoms of space*, to use an expression dear to Smolin. And so we conceived the *GrailQuest* (Gamma Ray Astronomy International Laboratory for QUantum Exploration of Space-Time) experiment (Burderi et al. 2021). A pathfinder of *GrailQuest* is already under development through the HERMES (High Energy Rapid Modular Ensemble of Satellites) project: a fleet of six 3U cube-sats to be launched by the end of 2023 (Burderi et al. 2020).

We plan to observe, with a network of satellites from space, Gamma Ray Bursts, the flashes of gamma light that herald the final collapse of the stars beyond the Event Horizon, the most intense explosions from the far reaches of the Cosmos. With an overall huge effective area and very high temporal resolution, we plan to measure the small delays (few microseconds) imparted by the granular texture of Space-Time to photons of different colors (in the keV–Mev frequency range), at the end of a journey of billions of years from the borders of the Causal Universe. Moreover, *GrailQuest* and HERMES will allow to perform temporal triangulation of impulsive events with arc-second positional accuracies: an extraordinary sensitive X-ray/Gamma all-sky monitor crucial for hunting the elusive electromagnetic counterparts of Gravitational Waves, that will play a paramount role in the future of Multi-messenger Astronomy. The main features of the *GrailQuest* project are shown in Figure 3

Again we were following the idea that the entire Universe is the laboratory where Nature has prepared the appropriate experiments to solve its deepest enigmas.

This is the path traced by Nichi, and his legacy to us echoes in the words of the Icelandic alchemist, hero of the novel *Journey to the Center of the Earth* by Jules Verne, who urges the scientist to undertake a perilous journey: *"Descende, audax viator, et terrestre centrum attinges. Quod fecit, Arne Saknussemm."* I like to believe that you too, friend and daring traveler, like the intrepid Arne, may have laid, at the end of your journey, the clear and curious gaze, which unites children and men of science, on the wonderful secrets of the world.

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