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Original Paper

From No-signaling to Spontaneous Localization Theories: Remembering GianCarlo Ghirardi

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1. Life and Achievements

GianCarlo Ghirardi passed away on June 1st, 201. He would have turned 83 on October 28, 2018. He was without any doubt one of the most prominent theoretical physicists working on the foundation and the philosophy of quantum mechanics. He was born and raised in Milan, where he earned his Ph.D. in theoretical physics in 1959. After four years he moved to Trieste, where he later became Full Professor. He has been director of the department of theoretical physics there and he was president of “Consorzio per la Fisica”, also in Trieste. Moreover, he contributed to found and to develop the Italian Society for the Foundation of Physics, and he actively contributed to the Abdus Salam International Centre for Theoretical Physics, first as a researcher, then as a professor, and finally as the head of its Associateships and Federation Scheme. Among the honors he received, one can count the “Sigillo d'argento” from the province of Trieste, awarded in 2014, for his research and teaching activities, for his devotion in promoting physics, and for his dissemination activity. Moreover, just recently he received the 'Spirit of Salam Award' for supporting scientists from developing countries.

In his life, he wrote more than 200 scholarly articles and two books: “Symmetry Principles in Quantum Physics”, together with Luciano Fonda (Fonda and Ghirardi 1970), and “Un'occhiata alle carte di Dio” (Ghirardi 1997), which has sold 20,000 copies and later was translated by Princeton University Press under the title “Sneaking a Look at God's Cards” (Ghirardi 2005). GianCarlo was known first and foremost for his contribution to the foundation of quantum mechanics.

2. Nonlocality, No-signaling and No-cloning

GianCarlo arrived to quantum foundations after some years spent working on nuclear physics during which he established, together with his friend Alberto Rimini from the University of Pavia, and other collaborators including his colleague Tullio Weber, some important results on the number of possible bound states for a given interaction (Ghirardi and Rimini 1965). Presumably, this work on different levels of description, as well as some new readings which included Bernard d'Espagant's book (1965), led GianCarlo to gain interest in the foundations of quantum mechanics. Not surprisingly, his distinctive enthusiasm managed to convince Rimini and Weber to work with him on that.

His first important contributions to this field are connected with quantum nonlocality and the possibility of superluminal signals. Indeed, it is somewhat ironic that GianCarlo was born in 1935 and spent all his life working on the foundation of quantum mechanics and on its compatibility with relativity theory. In fact this was the year in which Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) published their famous paper (Einstein, Podolsky and Rosen 1935) and during the same year Schrödinger published the paper in which he describes his famous "Schrödinger's cat paradox", also known as the measurement problem (Schrödinger 1935), to which GianCarlo proposed a solution, as discussed in the next section. Be that as it may, EPR proved that if quantum mechanics were complete, then the world must be nonlocal. Take two particles in a spin singlet state emitted in opposite direction by a source. Two experimenters take spin measurements at each side, and it turns out that the results at both ends are perfectly anti-correlated. EPR asked for the origin of such anti-correlations: they are either the product of 'pre-existing' anti-correlations at the source, or they are the result of 'instantaneous' communication between the two particles once detected. They regarded the second, nonlocal, option as unacceptable because incompatible with relativity since it implies the existence of an instantaneous interaction between two (space-like) separated places. Because of this, they concluded that the particles had anti-correlated properties before the measurements. If so, quantum mechanics is incomplete because the theory does not specify these properties, which nonetheless exist. However, as later was shown by John Stuart Bell (Bell 1964), the locality assumption in EPR's reasoning, namely the assumption that the behavior of something does not affect the behavior of something else spatially separated from it, was to blame. As a consequence, nothing could be concluded on whether quantum theory was complete or not. Bell started from the conclusion of EPR that there are 'pre-existing' properties and went to compute some measurable consequences of a theory which would specify such properties. It came out that the empirical predictions were at odds with the ones of quantum mechanics and thus one could perform a sort of crucial test. This was in fact done (Freedman and Clauser 1972, Aspect *et al.* 1981, 1982), and it falsified local theories as the ones envisioned by Einstein, Podolsky and Rosen. That is, any empirically adequate theory would have to be nonlocal. So the problem was then how to reconcile quantum nonlocality with relativity. At the time, it was even more problematic because some had argued that quantum mechanics would permit superluminal signaling: that is, not only there are nonlocal influences, but they could be used to transmit information. In 1980, however, GianCarlo, together with Rimini and Weber, proved that quantum nonlocality cannot be used to send information faster than light (Ghirardi, Rimini and Weber 1980). This theorem is now called no-signaling theorem. Moreover, in 1981 GianCarlo was refereeing a paper in which the authors were trying to prove that quantum mechanics would allow superluminal signaling, and he proved in his referee report what is now known as the no-cloning theorem, proving that it is impossible to create an identical copy of an arbitrary unknown quantum state. GianCarlo's proof in the referee report was one year earlier than the papers that are usually regarded as the ones discovering the theorem (Dieks 1982, Wootters and Zurek 1982), considered one of the milestones of quantum information theory, even if it was published later (Ghirardi and Weber 1983).

3. The Measurement Problem and Spontaneous Localization Theories

After working on nonlocality and no-signaling, in 1986, together with Rimini and Weber, GianCarlo proposes a theory which is now known as the Ghirardi–Rimini–Weber (GRW) theory (Ghirardi, Rimini and Weber 1986) as the solution of the (infamous) Schrödinger cat paradox, also known as the measurement problem. This is, without any doubt, GianCarlo's main contribution to the foundations of quantum mechanics.

The measurement problem has been around since 1935: if every physical system is completely described by an object, the wavefunction, which evolves according to Schrödinger's equation, then because of the linearity of this equation we should observe macroscopic superpositions. Since we do not observe them, quantum mechanics needs to be revised. In the 1950s some solutions to this problem were proposed, most notably Bohmian mechanics (Bohm 1952) and the Many-Worlds theory (Everett 1957), which respectively are taken to 'add' something to the description provided by the wavefunction, and to make sense of macroscopic superpositions by stipulating they suitably exist in other undetectable worlds. On top of this, GianCarlo, together with Rimini and Weber, proposed his solution to this problem, namely the GRW theory. It is also called spontaneous collapse or spontaneous localization theory because the wavefunction does not evolve according to the Schrödinger equation but it randomly collapses into one of the terms of the superpositions and thus localizes in a small region of space.

Presumably, one of the problems that led GianCarlo to his theory was to reconcile the (classical) exponential decay law with quantum theory. In their 1976 paper, GianCarlo and his collaborators Luciano Fonda and Alberto Rimini provided a theory of unstable systems, and this led them to consider localization procedures (Fonda, Ghirardi and Rimini 1978). In their work, the wavefunction of the decay fragments underwent random localization processes at random times. In these papers the reduction processes were due to the interaction of the system with its environment. However these proposals can be seen as precursors of the GRW mechanism, in which the wavefunction localization is instead spontaneous and fundamental. Around the same dates, Philip Pearle (1976, 1979), Nicolas Gisin (1984), Lajos Diosi (1986) and others developed models to account of the wavefunction collapse in terms of a stochastic modification of the Schrödinger equation. However, they were not able to provide a general account, independent of the type of measurement performed. Also, there was the trigger problem (Pearle 1989): it was not clear how to make the localization effective for macroscopic objects but not for microscopic ones.

The breakthrough happened in 1986, when GianCarlo, together with Rimini and Weber, published their spontaneous localization theory which would allow for a 'unified dynamics of microscopic and macroscopic system'. In the GRW theory the wavefunction does not evolve according to the Schrödinger equation but stochastically localizes so that macroscopic objects are never found in macroscopic superpositions. The existence of such a theory was not obvious, because it has been shown (see, e.g. Gisin 1989) that nonlinear modifications of the Schrödinger equation without stochasticity lead to superluminal signaling, and thus are unacceptable. Therefore the proposal was received with great enthusiasm, especially by John Stuart Bell, who contributed to making the theory well known in the community (Bell 1987). The authors refer to their model as QMSL (Quantum Mechanics with Spontaneous Localizations), in which every physical system is subject at random times to random and spontaneous localization processes, which they called 'hittings'. This is, roughly, how it works: when a hitting occurs, the wavefunction (as a function of position) is instantaneously multiplied by an appropriately normalized Gaussian function of width d, which represents the localization accuracy. The localization center is random with probability given by the squared norm of the localized wavefunction (as to reproduce the quantum predictions). Also, it is assumed that the hittings occur at randomly distributed times, according to a Poisson distribution, with mean frequency f. In between hittings, the wavefunction evolves linearly according to the Schrödinger dynamics. This theory does not suffer from the trigger problem because the localization of one of the constituents of a macroscopic object amounts to the localization of the object itself. In fact the wavefunction of a macroscopic object can be thought as the product of the wavefunctions of its microscopic constituents, which are not zero only in one of the terms of the superposition. So that if one of the microscopic system undergoes localization near a give point, all the macroscopic superposition will also localize around the same point. The localization accuracy $d = 10^{-5}$ cm and the frequency $f = 10^{-16} s^{-1}$ were chosen so that macroscopic systems would undergo localization on average every hundred million years, while a macroscopic systems would undergo localization every 10^{-7} seconds. The original

GRW proposal worked only for nonidentical particles. However, the idea can be generalized in the framework of the so-called Continuous Spontaneous Localization models, or CSL (Pearle 1989; Ghirardi, Pearle, and Rimini 1990) in which the discontinuous jumps are replaced by a continuous stochastic evolution in the Hilbert space.

Notice that these theories are empirically distinguishable from ordinary quantum mechanics, so that one expects to find effect in superconducting devices, as well as loss of coherence in diffraction experiments with macromolecules and in opto-mechanical interferometers, and spontaneous X-ray emission from Germanium. For a review of the experimental work connected to the GRW theory and CSL models, see e.g. (Bassi and Ghirardi 2003), (Adler 2007), and (Bassi **et al.** 2013).

In the years that followed until his death, GianCarlo continued to develop and extend his theory, solving conceptual problems connected to it and working towards a relativistic model.

4. The Mass Density Field and Relativistic GRW Theories

I was never GianCarlo's student. I came to know of him for the first time because I read his book. At the time "Sneaking a Look at God's Cards" was first published, I had just graduated from University of Milan. I ended up defending a dissertation in nuclear physics because my idea of doing theoretical physics has been shattered after taking a class on quantum mechanics. In fact, in the class I was taught that observers create reality, scientific realism is impossible, and particles can have contradictory properties such as being 'here' and 'there' at the same time. At the time I was doing a master course in scientific communication at the University of Milan, the purpose of which was to learn how to explain complex scientific concepts clearly. An assignment had to do with quantum mechanics, so I remembers hopelessly wandering towards the University bookstore to get some distraction. And there it was! Close to the "The Fabric of Reality" by David Deutsch (1995), I found GianCarlo's book "Sneaking a Look at God's Cards". I bought them both and devoured them. They contributed to my rethinking of quantum mechanics, and ultimately were determinant in reshaping my career path. In fact, I realized that the questions I has been asking all along, while sitting in the class on quantum mechanics, were not stupid and they actually had answers. So I decided to pursue theoretical physics again. I am sure GianCarlo's work has inspired many others as well, students and not. I went on doing a Ph.D. in physics at the University of Genova with Nino Zanghì partly because I came to know his work by being mentioned in GianCarlo's book. I finally had the privilege of meeting GianCarlo for the first time during a conference in Ischia in 1999, when I was a first year graduate student. I met him again at another conference in Urbino in 2004 and his enthusiasm about the discipline of quantum foundations was even more contagious. We became friends since then, and had regular correspondence and exchange of ideas until GianCarlo died. On a personal level, I was particularly impressed by how GianCarlo was very laid back, so that one would not be afraid to be judged when talking to him. He was very modest and sweet, always willing to receive feedback and constructive exchange of ideas. Unfortunately, not many in physics were like him and this consideration was among the factors that made me decide to switch to philosophy. I therefore went to Rutgers, where other people mentioned in GianCarlo's book were working, including Tim Maudlin and Sheldon Goldstein.

Aside from proposing the GRW theory, I think that the most significant philosophical insight of GianCarlo was his introduction of the mass density field. Indeed, my philosophy Ph.D. thesis was on the structure of quantum theories, and I was most influenced by GianCarlo's work on the role of the mass density field in spontaneous localization theories. In fact, GianCarlo in 1995 published an article, together with Renata Grassi and Fabio Benatti (Ghirardi, Benatti and Grassi 1995), in which he argued that one would need to supplement the description provided by the GRW collapse mechanism by the specification of a (three-dimensional) mass density field, defined in terms of the wavefunction. GianCarlo and his collaborators contended that if the wavefunction correctly represented physical systems, then the distance in Hilbert space would be able to capture how states as represented by wavefunctions are physically different. However, this is not the case. Take, for instance the following three states: $|h>$, $|h^* >$ and $|t>$, where $|h>$ and $|t>$ represent different macroscopic properties of an object, such as being localized 'here' and 'there', while $|h^* >$ is a state identical to $|h>$, but for one particle being in a state orthogonal to the corresponding particle in $|h>$. Then, macroscopically, $|h>$, and $|h^* >$ are indistinguishable and different from $|t>$. Despite of this, however, the Hilbert space distance between $|h>$ and $|h^* >$ is equal to that between $|h>$ and $|t>$. As a consequence, GianCarlo and his collaborators concluded that macroscopic systems would be better represented by something other than the wavefunction, and they proposed a material field in three-dimensional space, dubbed the mass density field. The reasoning behind this proposal is connected to what is now called the configuration space problem: if the wavefunction represents physical objects, then physical space is configuration space, and we need to understand how we seem to live in three-dimensional space. GianCarlo argued that the wavefunction is not the right kind of mathematical object to represent physical entities, and that we need some *stuff* in three-dimensional space to ground any theory, like for instance the mass density field. If we follow this advice, the configuration space problem never arises and the one is left to investigate the (true) open problems with the GRW theory, namely its extension to the relativistic domain, or the origin of the spontaneous collapse.

I was heavily influenced by this part of GianCarlo's work, which contributed to my understating and developing the ideas behind the so-called primitive ontology approach to quantum theories. In this framework, physical entities are 'made up' by three-dimensional fundamental constituents, dubbed the primitive ontology of the theory, the mass density in GRW being one. Before the introduction of the mass density field, GRW seemed to be a theory about the behavior of the wavefunction. That is, in GRW matter was taken to be ‘made of’ wavefunctions. However, in GianCarlo’s mass density interpretation of his own theory, this is no longer true: matter is ‘made of’ the mass density field. Therefore there is a sense in which also in the GRW theory, as in Bohmian mechanics, we are ‘adding’ something to the description provided by the wavefunction. As a consequence, one can see how Bohmian mechanics and the GRW theory actually share a common structure: there is matter, represented by some stuff in three-dimensional space, namely the primitive ontology; and then there is the wavefunction. Following this lead, the nature of the wavefunction needs to be revised: if it does not directly represent physical objects, what is it? This is part of my current research project, which has obviously been influenced, inspired and informed by GianCarlo’s insights, which however did not have a definite opinion about it.

Be that as it may, understanding theories in terms of their primitive ontology is particularly relevant when considering how to extend a physical theory outside its domain of validity. In the case of GRW, considering different primitive ontologies has led to different models of wavefunction spontaneous localization theories. The first relativistic invariant GRW model was proposed by Roderich Tumulka (2006). It is a theory for *N* non-interacting distinguishable particles, based on a multi-time wavefunction evolving according to Dirac-like equations. However the theory is not about the behavior of the wavefunction but rather is about the distribution of the locations of wavefunction collapse, dubbed ‘flashes,’ which therefore are the primitive ontology, as suggested by Bell (1987). Moreover, GianCarlo, developing some of his earlier ideas (Ghirardi 2000), and collaborating with Daniel Bedingham, Detlef Dürr, Sheldon Goldstein, Roderich Tumulka and Nino Zanghì (2014), has proposed a relativistic invariant GRW theory for a mass density primitive ontology.

GianCarlo, at the time of his unexpected death, was still scientifically active and he had just finished a book on the importance of symmetries not only in science but also in art and music. He will be greatly missed.

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