DOI: 10.1364/JOSAB.536847

Journal of the Optical Society of America B
OPTICAL PHYSICS

The Jaynes–Cummings model: 60 years and still counting

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Received 15 July 2024; posted 15 July 2024; published 25 July 2024

2023 marked the 60th anniversary of the Jaynes–Cummings model, a foundational model in quantum optics. Over the years, its importance has expanded beyond traditional light–matter interaction systems, such as cavity QED. This special issue presents a collection of articles that showcase the evolution of the model's applications, blending traditional topics with contemporary developments.

https://doi.org/10.1364/JOSAB.536847

1. INTRODUCTION

While related spin-boson models had been discussed earlier, what became known as the Jaynes–Cummings model (JCM) was based on a paper by E.T. Jaynes and F. W. Cummings in January 1963 and consisted of a two-level atom coupled to a single mode of the electromagnetic field. It was intended to launch a semi-classical description of the interaction between light and matter and the discussion of the two authors laid more emphasis on a "semiclassical theory, (which) when extended to take into account both the effect of the field on the molecules and the effect of the molecules on the field, reproduces almost quantitatively the same laws of energy exchange and coherence properties as the quantized field theory" [1]. This seemingly simple model, however, offered profound insights into fundamental mechanisms governing the light–matter interaction in the quantum realm, while also being amenable to an exact, analytical solution [although under the so-called rotating wave approximation (RWA)].

Nevertheless, the 1963 paper did not receive much attention in the first decade following its publication, as shown in Fig. 1. It was only in the second decade of its existence that it began to attract the attention of researchers who discovered signatures of coherence in the model, the most notable being the collapses and revivals of atomic inversion for an initial coherent state of light. Furthermore, scientific endeavors focused on significant generalizations like the Tavis–Cummings and Dicke models, the latter having been introduced in 1954. In the 1980s, experimental work in cavity QED brought the model into the laboratory, and the field really took off in the 1990s with the advent of quantum information science. Just before the turn of the century, groundbreaking experiments were conducted in both cavity QED and trapped ion systems. Figure 1 illustrates this trend by showing the number of articles, books, proceedings, and other publications mentioning the term "Jaynes–Cummings." This yearly increase in citations has continued, driven by groundbreaking advances and discoveries. For instance, the early 2000s saw the emergence of circuit QED as a promising platform for implementing QIP schemes, due to its scalability and low decoherence times. In the last decade, the model has become more integrated into various condensed matter systems.

Stimulated primarily by experimental advances, JC physics in the last decade has increasingly focused on new physical systems described by single boson modes coherently coupled to few-level systems. A plethora of such configurations have been demonstrated, highlighting the exquisite control achieved over a regime where the addition or subtraction of a single quantum significantly impacts observable physics. In parallel, novel theoretical directions have emerged, including thorough discussions on the integrability of paradigmatic models of light–matter interaction. Researchers have taken the coupling strength into new regimes where traditional QED approximations break down. Exploring these new parameter regimes has also led to a reassessment of the model's underlying approximations, raising fundamental questions about aspects like gauge invariance. Six decades since its inception, the Jaynes–Cummings model, a fundamental model of quantum optical resonance, continues to

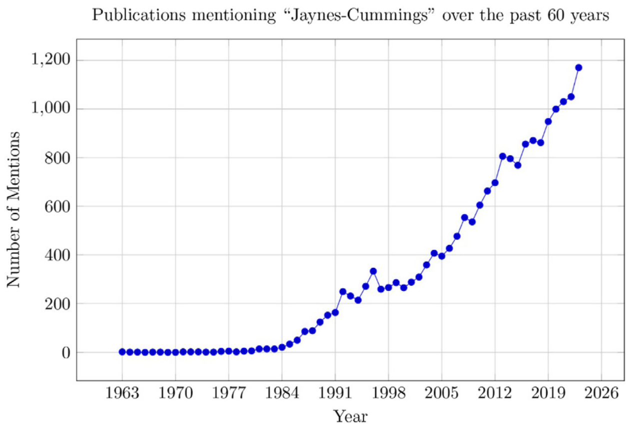

Fig. 1. The number per year of articles, proceedings, books, and other publications using the term Jaynes–Cummings from 1963 to 2023. Data are sourced from Google Scholar.

thrive in various fields of modern physics, with ample room for future development.

2. PAPER SUMMARIES

This feature issue demonstrates the enduring relevance of the Jaynes–Cummings model (JCM), with its mix of papers from the following topics:

Correlations (Corr)
Decoherence (De)
Dressed states (DS)
Driven JCM (DJCM)
Molecules in cavities (MC)
Non-classical light (NonCl)
Photon blockade (PB)
Quantum phase transitions (QPT)
Quantum control (QC)
Rabi model (RM)

Within quantum optics, Elliott and Parkins [2] reveal a wide gamut of possible negative Wigner distributions for experimentally relevant configurations of cavity QED (NonCl). At the same time, keeping up with the nonclassicality of the JC scattering and in the spirit of collapse and revivals, Hernández-Sánchez *et al.* [3] focus on the atomic inversion in the driven extension of the model, when the cavity is prepared in a thermal state (DJCM). Moving now to closely related formulations of light–matter interaction, Braak *et al.* [4] demonstrate the existence of bound states incorporated into the continuum when a dynamic Stark shift is included in the quantum Rabi model (RM).

Changing target to quantum information processing, an exact solution for the scattering of a two-photon wavepacket by a three-level atom in a waveguide is offered by Lopes da Silva and Valente (QC) [5].

Kurkó *et al.* [6] discuss the significance of the neoclassical theory of radiation in capturing key aspects of the bistability accompanying the photon-blockade breakdown (PB, DJCM). Further on, the very JCM is put to test when free-space decay channels are being blocked, in the work of Blaha *et al.* (De) [7].

In the realm of light-induced phenomena, Peyton *et al.* [8] use the quantum Rabi model as a basis of comparison with the Pauli–Fierz Hamiltonian employed in the study of cavity-molecule systems (MC). Similar systems are also the focus of work by Lydick *et al.* [9], who consider the effects of multi-modes on the cavity Tavis–Cummings model.

A historical perspective of the JCM can be found in our issue by some of the pioneers in the field [10]. During the last decade of JC physics, fundamental questions regarding the relevance of the model have been raised, which is discussed in the tutorial by De Bernardis *et al.* [11].

Bertassoli and Vidiella-Barranco [12] return to a well-known field related to the JCM, namely, trapping states. They focus on atomic trapping states and their impact on resonance fluorescence (DS). Lydick *et al.*, like Peyton *et al.*, explore the relatively new field of polaritonic chemistry, where the novelty lies in the fact that molecular dynamics and chemical reactions can be manipulated by coupling the molecules to quantized cavity fields (MC). Due to the complex internal structure of the molecules, the validity of standard approximations of the JC or Tavis–Cummings models can be questioned; Lydick *et al.* address this issue for the single-mode approximation. Algebraic methods have proven powerful when analyzing the JCM; Kafuri *et al.* [13] examine the anisotropic quantum Rabi model through the lens of Lie theory (RM).

Christiansen *et al.* [14] demonstrate the versatility of the JCM by showing how it can, in conjunction with the cascaded-quantum-systems formalism, provide insights and predictions for the interaction of a two-level emitter with a traveling pulse of quantum light, rather than just the traditional single-field mode (NonCl, De).

Waveguide-coupled arrays of single-atom cavity QED systems, each described by the JCM, are of interest in numerous, topical contexts, including strongly correlated many-body quantum physics, and Berndsen *et al.* [15] explore the transport properties of single photons in both periodic and disordered arrays of such systems (QC).

Further to the general theme of many-body quantum systems, but returning to a single cavity mode, Karmstrand *et al.* [16] examine in detail the dressed states of the driven, damped Tavis-Cummings model for just a few emitters and the collapse of the associated eigenenergies at a drive strength linked to a dissipative quantum phase transition in the system (PB, QPT).

In the opposite limit of a large number of emitters, Beloiarov *et al.* [17] demonstrate the utility of semiclassical methods for the analysis of spectra in the single- and two-photon Tavis–Cummings models (DS).

Maximally efficient single-photon sources are vital to numerous, emerging quantum technologies. Hughes *et al.* [18] present a comprehensive study of the optimization of single photon extraction from a prototypical emitter-cavity system, the description of which is based upon the JCM (NonCl, QC).

Effective transfer of quanta of excitation among coupled atomic or molecular systems is another area of interest to quantum technology, as well as to chemical and biological systems. Aiyejina *et al.* [19] consider the photon-mediated transfer of single or double excitations in dimer and trimer three-level systems (QC), and Wyke *et al.* [20] consider the transfer efficiency of various light-harvesting models comprising a trimer ring coupled to an acceptor atom (QC). Three-level atoms are also discussed within optomechanics by Kibret *et al.* [21], who assess the impact of the number of atomic levels on the entanglement generation between the cavity and the mechanical oscillator mode (QC).

Solid state cavity QED systems based on quantum dots and excitons are a further, prominent platform for the JCM, but offer up new challenges in the form of structured reservoirs and non-Markovian dissipation. Lira and Sanz [22] study the generation of Schrödinger cat states of light via a dispersive JCM interaction and their evolution in such an environment (NonCl, De).

A method to diagonalize the JCM via a unitary transformation is presented by Barnett and Dalton [23]. They introduce "dressed operators" that act directly on the atom-field, dressed states, allowing definition of interesting constructions such as the "JCM coherent states," the eigenstates of the dressed operators (DS).

Luo and Yu [24] assume that the JCM atom is under the action of a "structured environment," formed by a cavity field (direct coupling) and a bath coupled to the cavity field (indirect coupling). They study two mechanisms to suppress decoherence: one using control pulses and another that recovers the initial state (Petz maps) (De).

Correlations are inherent in the JCM. Mavrogordatos [25] addresses the multiphoton emission dynamics in the JCM by examining wave-particle correlations. This reveals a significant asymmetry in the quantum fluctuations of light as well as subtle aspects due to quantum interference in the system (Corr, PB).

Second-order correlation functions can be useful to study non-classical correlations in interbeam frequency components, as discussed by Maslennikov *et al.* [26]. They find that there are some frequency components where the light behaves classically while at others it does not (Corr).

A variation of the JCM (and also the Lipkin–Meshkov–Glick model) is investigated by Larson [27], who considers a periodic driving, using a Floquet theory approach to study the rich dynamics presented by both models. In the LMG model with slow driving, random jumps in the magnetization occur, a clear signature of chaotic behavior (DJCM).

Comparisons between the Rabi model and the JCM are recurrent in the literature, and here Coleman and Twyeffort [28] make a thorough comparison of their semiclassical limits. Concerning the validity of the RWA, the authors conclude that the "dynamical validity" does not generally follow from the "spectral validity" (RM).

3. PERSONAL REFLECTIONS ON THE JAYNES–CUMMINGS MODEL

Antonio: I first heard about the JCM from Peter Knight during my PhD. I was awestruck not only by its simplicity but also because it offered a nonperturbative approach, providing significant insights into the fundamentals of light–matter interaction. At that time, I was studying the properties of a few quantum states of light, notably the Schrödinger cat states, and soon enough I wanted to investigate the dynamics of the atom and the light field; particularly, how one could distinguish between statistical mixtures of coherent states and pure states (Schrödinger cats). Since then, the JCM has accompanied me in a great deal of my work in various contexts, and I have closely followed the multitude of applications and diverse areas covered by this remarkable model over the years. Now I feel privileged to celebrate its 60th anniversary in my role as editor of this Feature Issue.

Jonas: My first encounter with the JCM was during the early stages of my PhD under the supervision of Stig Stenholm. Throughout my PhD, the JCM was my primary focus, and working with Stig allowed me to hear numerous anecdotes, often directly from those involved (my favorite being the discovery of collapse-revivals). Although my research interests have expanded since then, the JCM has remained a significant part of my work. This led to the publication of the monograph *The Jaynes–Cummings Model and Its Descendants*, coauthored with Themis Mavrogordatos [29], and my role as an invited editor for a special issue celebrating the model's 50th anniversary. Now, a decade later, I am honored to serve in the same capacity for its 60th anniversary. Witnessing the advancements in the field over the past 10 years has been truly inspiring.

Scott: While I was familiar with the JCM from early on in my graduate studies in quantum optics with Dan Walls and Crispin Gardiner, it was during my first postdoc at JILA with Peter Zoller in the early 1990s that I really got to work with the JCM myself. And this was indeed a fascinating time to get involved with this model, as it played a central role in the explosion of interest in quantum state engineering using both cavity QED and trapped ions, which was of course intimately connected with the remarkable genesis of quantum information science as a practical technology. Nowadays, I continue to marvel at how the JCM remains central to so much research, both theoretical and experimental, and at its accessibility to undergraduate and graduate students, enabling them to understand key aspects of many quantum technologies and to get involved so readily in novel and topical research of their own. This only heightens their enthusiasm for this field and, as a supervisor, I can think of no better reward.

Themistoklis: As I started making my first steps into quantum optics, I quickly realized that the JCM holds the key to the reappraisal of wave/particle duality, a longstanding subject since the development of the old quantum theory, substantiating Planck's suggestion [30]: "I believe one should first try to move the whole difficulty of the quantum theory to the domain of the interaction of matter with radiation." Nowadays, due to the exquisite control acquired over cavity and circuit quantum electrodynamics architectures, the breakdown of photon blockade—at the core of the open JCM phenomenology as detailed in [31]—can be operationally ascertained via individual quantum realizations. These realizations are bound to be generated in a contextual manner, revealing the complementary aspects wave/particle duality takes on, in a regime where quantum fluctuations produce a continual disagreement with semiclassical predictions.

We sincerely hope you will share our enthusiasm when reading the special issue!

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