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Dynamics of epidemic spreading with vaccination: Impact of social pressure and engagement

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HIGHLIGHTS

- Epidemic spreading with vaccination under the impact of opinion dynamics.
- Vaccine can give permanent or temporary immunization to the individuals.
- We determine the conditions for the occurrence of outbreaks.
- Detailed analysis of the stationary states.

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ABSTRACT

In this work we consider a model of epidemic spreading coupled with an opinion dynamics in a fully-connected population. Regarding the opinion dynamics, the individuals may be in two distinct states, namely in favor or against a vaccination campaign. Individuals against the vaccination follow a standard SIS model, whereas the pro-vaccine individuals can also be in a third compartment, namely Vaccinated. In addition, the opinions change according to the majority-rule dynamics in groups with three individuals. We also consider that the vaccine can give permanent or temporary immunization to the individuals. By means of analytical calculations and computer simulations, we show that the opinion dynamics can drastically affect the disease propagation, and that the engagement of the pro-vaccine individuals can be crucial for stopping the epidemic spreading. The full numerical code for simulating the model is available from the authors' webpage.

1. Introduction

Epidemic spreading and opinion formation are two dynamical processes that have been attracted the interest of the scientific community in the last decades [1–10]. The interest of physicists varies from theoretical aspects like critical phenomena [11–16], stochasticity [17,18], universality [19] and multiple phase transitions [20], to practical questions like the detection of the zero patient [21], super spreaders [22], effects of self isolation [23] and others. More recently, the coupling of epidemic and opinion models has also been considered [24–27].

Regarding a vaccination campaign in a given population, the individuals consider some points in order to make the decision to take the vaccine or not. In the case when a considerable fraction of the population decides to not take the vaccine, the consequences for the whole population may be drastic. As an example, in 2010 the French government requested vaccine for H1N1 for 90 million individuals, but about 6 million of the vaccines were effectively used by the population, and in this

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case the disease has spread fast [28]. In this case, one can see that the public opinion can be a key feature in the diffusion of a disease in a given population, promoting the occurrence or the lack of an outbreak.

The public opinion about vaccination can be affected by economic factors. For example, we have a competition between the "cost" to become vaccinated (collateral effects, required time to take the vaccine, ...) and the injury caused by the disease when the individual does not take the vaccine (medication, money, miss some days of work, ...). In this case, the usual approach is to consider game theory or epidemiological-economic models [29,30]. However, usually the individuals/agents do not take into account only economic factors [24–26,31–33]. As discussed in Ref. [34], *"if individuals are social followers, the resulting vaccination coverage would converge to a certain level, depending on individuals' initial level of vaccination willingness rather than the associated costs"*. In addition, in Ref. [35] it is discussed that *"assumptions of economic rationality and payoff maximization are not mandatory for predicting commonly observed dynamics of vaccination coverage such as the failure to reach herd immunity and oscillations between high and low levels of coverage"*. Related to social norms, the authors in Ref. [36] propose that *"including injunctive social norms will enable models of parental vaccinating behavior for pediatric infectious diseases to better explain the whole range of observed vaccinating behavior, including both vaccine refusal and the high vaccine coverage levels so commonly observed"*. Indeed, some other works have shown that individuals are influenced by their social contacts in the process of opinion formation about a vaccination process [37,38]. In this case, in this work we consider an opinion formation process coupled with an epidemic dynamics where vaccination is taking into account. Our target is to investigate how the density of Infected individuals in short and long times is affected by the social pressure and the engagement of the individuals regarding the vaccination. Thus, we are interested in answer some theoretical and practical questions:

(i) What is the effect of social pressure and engagement in the epidemic spreading process?
(ii) What are the conditions for the occurrence of epidemic outbreaks in short times?
(iii) What is the critical initial density of pro-vaccine individuals that can avoid the occurrence of such short-time outbreaks?
(iv) The disease will survive in the long-time limit?

The answer for these questions are given in the next sections.

2. Model

An individual's willingness to vaccinate is derived from his perception of disease risk and vaccine safety. However, the interactions among individuals in small groups will also affect the decision of the individuals to take or not the vaccine. In this case, we will consider an epidemic dynamics coupled with an opinion dynamics regarding the vaccination. Thus, we consider a fully-connected population with N individuals or agents, that can be classified as follows:

- Opinion states: Pro-vaccine (opinion $o = +1$) or Anti-vaccine (opinion $o = -1$) individuals;
- Epidemic compartments: Susceptible (S), Infected (I) or Vaccinated (V) individuals.

Each opinion is supported by a given fraction of the population, namely f_{+1} and f_{-1}, representing the fraction of Pro-vaccine and Anti-vaccine agents, respectively. We define the initial density of $+1$ opinions as D, that is a parameter of the model, and in this case the density of -1 opinions at the beginning is $1 - D$. There are many models of opinion dynamics in literature [6–8,16,28,39–46], and as a simple modeling of such dynamics we considered that the opinion changes are ruled by the majority-rule dynamics [46,39], i.e., we choose at random a group of 3 agents. If there is a local majority (2×1) in favor of one of the two possible opinions, the individual with minority opinion will follow the local majority. In this case, we are considering a mean-field formulation for the opinion dynamics. In the following we will see that the epidemic dynamics is also defined at a mean-field level. Despite the simplicity of a mean-field approach, it allows us an analytical treatment, that is important to a better understanding of a new model. Topologically, the mean-field approach corresponds to a fully-connected population, where each individual interacts with all others. In this case, it is also a realistic situation thanks to the modern communication networks [47]. Finally, it has been discussed that one can capture most of the dynamics of an epidemic on a real social network using only mean-field calculations [48].

Regarding the epidemic dynamics, we made some assumptions. First of all, the opinion of an agent about the vaccination process determines his behavior regarding the decision to take the vaccine or not [6,9,24,25,29,31]. As discussed in Ref. [31], "after conducting large scale studies on the acceptance of the Influenza vaccine, Chapman et al. [49] conclude that perceived side-effects and effectiveness of vaccination are important factors in people's decision to vaccinate". *We also considered that at the same time the disease is introduced in the population, a mass vaccination campaign is started. This is a realistic assumption, since usually the governments act fast in order to avoid disease outbreaks. For simplicity, we did not consider competition for doses. Finally, we considered as some authors* [35] *that both dynamics (opinion and epidemic) occurs at the same time scale, i.e., the opinions evolve in the population due to interactions among agents, and at the same time a vaccination campaign occurs and the individuals may move among the epidemic compartments, that are defined in more details in the following. All these assumptions simplify the problem and makes the following analytical treatment easier. Furthermore, they are realistic, and were also considered by some authors from epidemiologists to mathematicians* [6,31,35].

Now, let us elaborate upon the coupling of the two distinct dynamics (opinion and epidemic). Fig. 1 shows an schematic representation of the dynamics. The Pro-vaccine agents (opinion $o = +1$) take the vaccine with probability γ. This parameter can be viewed as the engagement of the individuals regarding the vaccination campaign, i.e., it measures the tendency