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Can informational thermal physics explain the approach to equilibrium?

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Abstract
In this paper I will defend the incapacity of the informational frameworks in thermal physics, mainly those that historically and conceptually derive from the work of Brillouin (Science and information theory, Academic Press, New York, 1962) and Jaynes (Phys Rev 106:620–630, 1957a), to robustly explain the approach of certain gaseous systems to their state of thermal equilibrium from the dynamics of their molecular components. I will further argue that, since their various interpretative, conceptual and technical-formal resources (e.g. epistemic interpretations of probabilities and entropy measures, identification of thermal entropy as Shannon information, and so on) are shown to be somehow incoherent, inconsistent or inaccurate, these informational proposals need to 'epistemically parasitize' the manifold of theoretical resources of Boltzmann's and Gibbs' statistical mechanics, respectively, in order to properly account for the equilibration process of an ideal gas from its microscopic properties. Finally, our conclusion leads us to adopt a sort of constructive skepticism regarding the explanatory value of the main informationalist trends in statistical thermophysics.

Keywords Non-equilibrium statistical mechanics · Jaynes · Brillouin · Epistemic parasitism · Information-theoretical explanations

1 Introduction

One of the central problems in thermal physics has been to explain how and why systems that are far from their state of thermal equilibrium tend to approach it. In fact, the approach of a physical system to its thermal equilibrium state is usually one of the main characteristics of the thermal behavior of some physical systems

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(Albert 2000), and therefore a cornerstone (or even 'Law') of this particular domain of physics. A relatively simple and quite illustrative case of a process of approximation to equilibrium or 'equilibration' is found in the expansion of a gas in a large vessel when it is initially distributed in a small corner of the vessel.[1]

Since the late 1950s, mainly due to the publication of Shannon's information theory (Shannon and Weaver 1949), we have seen a rapid rise in what can be called 'informational' approaches of thermal physics within the scientific community. These could be mainly characterized by the use of different information concepts (mainly, the everyday notion and Shannon's quantitative measure) and formal information-theoretical (IT) tools to model, describe, explain or predict the dynamic evolution and macroscopic properties of physical systems with thermal behavior. During the second half of the twentieth century, the hope that informational techniques and theories could explain certain physical phenomena that were not yet understood increased exponentially, which led in the 1990s and 2000 to extreme optimism regarding the knowledge of physical reality provided by these informational proposals. The following quote is a clear example of this:

> The laws of information had already solved the paradoxes of thermodynamics; in fact, information theory consumed thermodynamics. The problems in thermodynamics is, in truth, a special case of information theory. Now that we see that information is physical, by studying the laws of information we can figure out the laws of the universe (Seife 2007, p. 87).

In this paper I will argue that the radical informational optimism regarding thermal physics embodied in the above quote cannot be justified on the basis of its success in explaining thermophysical phenomena. In particular, I will argue that the two main groups of informationalist approaches are incapable of offering a robust and physically meaningful explanation of the relatively 'simple' equilibration process of a gas (just detailed above) beyond that already offered by non-informational statistical mechanical formalisms. Such approaches can be broadly classified into two groups, namely those perspectives that identify information with entropy and those that assume that entropy and information (whatever the concepts used) are complementary. As we will see, the most relevant proposal of the first group will be that of Edwin Jaynes (1957a, b), unifying statistical mechanical entropy and Shannon's information; while that of the second group will be that of Léon Brillouin (1962), defending that information is nothing but negative entropy.

The plan we will follow is as follows. In Sect. 2 we will describe the treatments of the equilibration process of a gas by the statistical mechanics of Boltzmann and Gibbs, outlining the basic elements of these formalisms. Next, we will present Brillouin's informational proposal (Sect. 3) based on the Negentropy Principle and Jaynes' formalism (Sect. 4) based on the MaxEnt principle, as well as their respective treatment of the approach of physical systems to thermal equilibrium. In Sect. 5 we will evaluate the factors (interpretative, conceptual and formal) of both informational approaches to the generation of robust and physically significant explanations of the equilibrium

[1] Suppose that the gas is initially in a sub-volume of the container and that we eventually remove the barrier that separates the gas from the entire volume of the container. As soon as the barrier is removed, the gas begins to expand throughout the container until it reaches its state of thermal equilibrium.

process. In the last section we will argue that both Brillouinism and Jaynesianism can be understood as 'epistemic parasites' of Boltzmann's and Gibbs' statistical mechanical formalism, respectively, while the explanatory capacity of the former depends intrinsically on the explanatory power of the latter.

2 The thermal physics of the approach to equilibrium

One of the fundamental ideas for thermal physics, a discipline that encompasses both thermodynamics and statistical mechanics, is that any isolated system that is far from thermal equilibrium will progressively and spontaneously evolve towards that state in a certain period of time (Frigg and Werndl 2012). This can be called the 'Zero Law' of thermodynamics (e.g. Uffink 2007, footnote 6). Although historically this thesis has often been given, it should not be identified with the content of the famous Second Law, since the latter states (roughly) that the entropy of a system cannot be decreased, not that every thermal system must approach a particular state. Those irreversible processes by which systems approach thermal equilibrium are studied in the discipline known as classical thermal physics (although fascinating, we will obviate here its quantum dimension) of non-equilibrium, either in its thermodynamic or statistical mechanics aspect.

A paradigmatic example of an equilibrium process is found, as mentioned in the previous section, in the adiabatic expansion (without transmission of heat or matter with the medium) of an ideal gas from a minuscule volume to a much larger volume, as represented in Fig. 1. For example, suppose that all the gas (represented in a continuous form) is initially found in a small corner[2] of volume V' of a vessel with volume V" and we let the gas evolve spontaneously. According to the predictions of thermal physics (both the Second Law and the Zero Law), the gas will evolve for a certain time until it is evenly distributed and reaches thermal equilibrium at V". But how can we account for this process? Within the thermophysical study of the processes of approaching equilibrium we find an enormous variety of theoretical treatments of this phenomenon: ergodicity theory, thermodynamic limit theory, coarse-graining, and so on; see Uffink [2007]). However, we will focus in this section on the main proposals found in the statistical mechanical literature, namely that of Boltzmann and Gibbs, in the sense that analyze thermal processes from the properties of microscopic components of systems and certain probabilistic relationships.

2.1 Approach to equilibrium from Boltzmann's statistical mechanics

The treatment of the thermal equilibrium approach within Boltzmann's statistical mechanics[3] (henceforth 'BSM') is interesting. We will start from a 6 N-dimensional

[2] Although in the literature we can find this ubiquitous example except with a container with a partition in the middle (Shenker 2020), here we propose instead that the process can be carried out wherein the partition would be located in one small corner of the container just to 'visually' emphasize the process of a gas free expansion.

[3] Note that here we will not expose Boltzmann's own explanation (Boltzmann 1909) of the approach to equilibrium, nor does he offer a single version (appealing to the ergodicity hypothesis, probabilistic

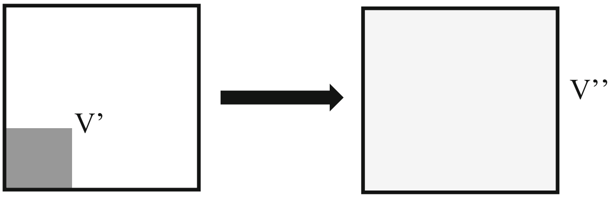

Fig. 1 Gas approaching thermal equilibrium via adiabatic expansion in V''

phase space Γ to describe the evolution of an individual system (paradigmatically a gas 'G' formed by N identical rigid spheres with diameter δ) towards the heat equilibrium state. From the standard BSM formalism phase space Γ is partitioned into different phase regions[4] corresponding to macrostates Γ_M, and on the other hand a measure μ (Γ) is taken (usually the Lebesgue measure) of the volume of phase points $|\Gamma_M|$, which in some sense corresponds to the number of microstates that describe exactly the deterministic data of position and velocity of the microscopic constituents of this system 'G'. Note that the Hamiltonian (deterministic and microscopic) dynamic evolution of the gas during a time interval generates a phase path or segment Γ_γ along phase space.

Another key element of BSM formalism is the assumption that the probability that the current microstate $\times$ of the system 'G' in time 't' is within phase region of a macrostate Γ_M is proportional to the volume $\mu(\Gamma_M)$ of microstates contained in that macrostate (encoding macroscopic properties of the gas 'G', such as its pressure P and its temperature T). From this assumption, the thesis is derived that the thermal equilibrium state of 'G' corresponds to the Γ_{Meq} macrostate with the largest phase volume in Γ (see Frigg [2009] for an exhaustive analysis of this thesis). With these ingredients we can now define the Boltzmannian entropy S_B of the current microstate x of the system in Γ_M as

$$k \, \mathrm{In} \, \mu \, (\Gamma_M) \tag{1}$$

Or in other words, as the natural logarithm of the phase volume of the macrostate Γ_M containing the current microstate x of the gas, multiplied by Boltzmann's constant k. In this sense, the thermal equilibrium macrostate not only corresponds to the region that most probably contains the current evolution of the system, but also corresponds to the macrostate with the highest entropy of Boltzmann S_B.

Once these fundamental elements of BSM have been exposed, we proceed to point out their treatment of the approach of a system as 'G' to thermal equilibrium through the irreversible process of expansion described at the beginning of this section. We first assume that our gas, as illustrated in the box on the left of Fig. 1, is initially (at instant

Footnote 3 continued
explanations, etc.) nor is there a historiographic consensus on this matter (see Uffink 2007), but we will offer the standard explanatory treatment as formulated by current Neo-Boltzmannian authors (Callender 1999; Albert 2000).

[4] As Frigg and Werndl (2011a) stressed, a formal and conceptual distinction must be made between 'macrostates' and 'phase regions' (as well as between 'microstates' and 'phase points'), although in the following we will use both terms indiscriminately for reasons of simplification and economy.

t_0) in a state far from equilibrium. In terms of the BSM, this means that the microstate of the system is initially in an extremely tiny phase region (analogous to the 'Past Hypothesis' described by Albert [2000] for the universe as a system). The dynamic evolution underlying the expansion process is represented by a phase trajectory that progressively moves through more volumetric regions from the initial tiny macrostate, eventually reaching the Γ_{Meq} region of greatest phase volume corresponding to the thermal equilibrium state of the gas.[5] Note that the latter is a statistical statement (it is 'extremely likely' that the phase trajectory will reach the equilibrium macrostate) conditioned by the probabilistic assumptions underlying BSM. This means that once phase trajectory Γ_γ has flowed into Γ_{Meq}, it can fluctuate out of this phase region with minimal probability. We conclude this section by noting that the Boltzmannian thesis that thermal systems far from equilibrium dynamically approach their thermal equilibrium macrostate with a huge degree of probability supports the so-called 'typicality conceptions' of the approach to thermal equilibrium, of which Frigg (2009) evaluated its explanatory power in this thermal context.

2.2 Approach to equilibrium from Gibbs' statistical mechanics

While BSM is based on describing the microstate of individual physical systems, Gibbsian statistical mechanics (GSM) is based on the notion of 'ensembles' (Gibbs 1902), which are nothing more than a set of virtual copies of a system with different properties, while keeping certain parameters constant. The ensembles (where the most used are those known as canonical, microcanonical and grand canonical, definable only for equilibrium states) are formally represented by probability distributions ρ over phase space. Based on these probability distributions it is possible to statistically calculate certain macroscopic properties (temperature, pressure, volume, etc.) of our paradigmatic gas 'G' from phase averaging and/or ensembles averaging of its values. Furthermore, according to GSM formalism, thermal equilibrium corresponds to that distribution in which the average values of ensembles are constant (also called 'statistical' or 'ensemble equilibrium'), i.e., they do not change throughout the dynamic evolution of ρ. With these resources we can define a first notion of Gibbsian entropy S_{Gf} as:

$$S_{\mathrm{Gf}}[\rho] = k \int_{\Gamma} \rho \log \rho \tag{2}$$

As it is known, this fine-grained notion presents great problems when dealing with the approach of systems to thermal equilibrium. While the evolution of the system is Hamiltonian, the dynamics traced by must satisfy the principle of Liouville or conservation of the phase volume. However, if the phase volume codified in ρ does not change during the evolution of 'G' throughout the irreversible process of expansion, this entropic measure $S_G[\rho]$ will remain constant against the predictions of thermodynamics. This is formally solved by introducing a partition or 'coarse-graining' of phase space Γ into equal-volume cells ω, with which by means of a phase averaging

[5] However, such a statistical statement lacks dynamic specificity (e.g. ergodic hypothesis) to fix how the phase path representing system will evolve.

procedure (whose theoretical legitimacy we will not evaluate in this paper) in which a new probability distribution is generated on the basis of the partition we derive a new entropy measure:

$$S_{G\omega}[\rho] = k\int_{\Gamma} \rho_{\omega} \log \rho_{\omega} \tag{3}$$

This new entropic measure does increase throughout the dynamic evolution of the system, although the reasons for this increase are controversial (Callender 1999). Therefore, the approximation of 'G' to thermal equilibrium according to GSM is achieved by eventually obtaining temporarily constant or stationary values (representing the ensemble equilibrium) in the dynamic evolution of a coarse-grained probability ρ_{ω}, obtained from averaging and phase space partitioning procedures from an initial probability distribution ρ.

Unlike the Boltzmannian approach, for the GSM context once the probability-represented ensemble reaches statistical equilibrium (and therefore also thermal equilibrium) it remains in that state permanently, according to the predictions of phenomenological thermodynamics. As Sklar (1993) emphasized, while individual systems have a minimal probability of fluctuating *outside* the macrostate of equilibrium (BSM), ensembles fluctuate *in* equilibrium without exception (GSM). Another important feature of Gibbs' statistical mechanics is its pragmatic ease in calculating macroscopic properties of physical systems against the enormous pragmatic difficulties and hard mathematical tractability presented by Boltzmann's formalism. This is why several pro-GSM authors (e.g. Wallace 2012; Luczak 2016) rely on real statistical mechanics practices (derivation of dynamic equations, evaluation of correlation functions, and so on) to give an explanatory account of the process of approaching equilibrium.

2.2.1 Information as negative entropy: Brillouin's informational statistical mechanics

One of the main systematic treatments of thermal physics from formalisms and informational concepts was carried out by Léon Brillouin (1962) during the 1950s. Unlike Jaynes' proposal (Sect. 4), his main concept of 'information' does not depend directly on Shannon's technical measure 'H', but on the notion of 'negative entropy' or simply 'negentropy' of a system, firstly outlined by Schrödinger[6] (2004). Brillouin distinguished between two concepts of information according to their physical relevance in scientific practice: (i) 'free information', such as that which can be encoded in probability distributions ρ (on which the entropy measure of GSM depends); and (ii) 'bound information', which is that which is encoded in the measure of the phase volume of macrostates $\mu(\Gamma_M) = W$ or 'Planck's' or 'Boltzmann's complexions[7]' or (on

[6] In fact, Brillouin appeals to Weaver's thesis (Shannon and Weaver 1949, footnote 1.) by which Boltzmann entropy can in fact be interpreted as an IT measure equivalent to Shannon entropy for uniform probability distributions. This of course constitutes both an anachronism (one cannot speak of a well-defined information theory before the 1940s) and a triviality (any quantity is not informational theory just because it is formally similar to it).

[7] This term is often used in the literature (e.g. Brillouin 1962) as the equivalent of 'equiprobable microstates'. Although historically the statistical mechanical idea of 'complexions' was developed by Planck, in the

which the entropy measure of BSM depends by definition). His proposal is articulated around the 'Negentropy Principle', by which linked and physically relevant information is defined not simply as negative entropy (as it is constantly assumed within the literature, since his concept of information would not apply the case of Gibbs entropy, be it fine-grained or coarse-grained) but as the complement of Boltzmann entropy or as the difference between two different values of this quantity (1962, p. 153):

$$\mathrm{I} = k \log \mathrm{W}_0/\mathrm{W}_1 = \mathrm{S}_\mathrm{B}(\mathrm{W}_0) - \mathrm{S}_\mathrm{B}(\mathrm{W}_1) \tag{4}$$

As several authors pointed out (Denbigh 1981; Earman and Norton 1999b) Brillouin's Negentropy Principle constitutes nothing more than an assertion of interconnectivity (as this is carried out is another matter) between complexion-encoded information and Boltzmann entropies. In Sect. 4 we will analyze the theoretical validity and explanatory value of Brillouin's principle. To illustrate his informational apparatus, the author analyzed our paradigmatic process of the expansion of an ideal gas (graphically illustrated in Fig. 1) as follows:

> Let us suppose that we have additional information on the state of the gas: for instance, we may happen to know that the gas, at a certain earlier instant of time, occupied a smaller number V'. This is the case if the gas is in a container V' and we suddenly open the connection with another volume V" […] After we open the volume V", the gas flows in, density oscillations takes place between the two volumes, and the steady state is progressively established with a uniform density through the volume V. Increase of entropy and loss of information proceed together. We may say that the gas progressively "forgets" the information (Brillouin 1962 , p.157).

For our argument, the process to be considered does not start with the gas in the V' container, since it would be in initial thermal equilibrium; on the other hand, the process of gas expansion starts just when there is no barrier between the two containers (Shenker 2020). A typical Brillouinian treatment would be the following. The initial state of the gas in V' at instant t0 would be represented by the 'W_0' complexions, on which we define its initial Boltzmann entropy as S_B $(\mathrm{t}_0) = k$ In W_0. Similarly, once the gas is uniformly distributed in V" it reached thermal equilibrium at instant t its state would be phase-space-represented with 'W_1', defining its final Boltzmann entropy as S_B (t) $= k$ In W_1. During the dynamic evolution of the gas in the interval t0–t, the total decrease of information would correspond to $-\Delta\mathrm{I}(\mathrm{t}_0$—t$) = k$ In $\mathrm{W}_1/\mathrm{W}_0$, or what is exactly the same (according to the Negentropy Principle), to the complement of entropy $\Delta\mathrm{S}(\mathrm{t}_0$–t) generated during the process. But, how could this amount of negative information explain the thermal behavior of the gas in its approach to equilibrium? The answer to this question is left for Sect. 4. However, first we should ask about the concept of information that is being used here. In the above quotation a phenomenon not highlighted by any commentator or critic of Brillouin's work is magnificently captured: the confusion between two radically different conceptions of information.

Footnote 7 continued
literature the expression 'Boltzmann's complexions' is frequently used. For this reason, we will use the latter option.

(B1) Complexion-encoded information (Epistemic interpretation)

On the one hand, the term ‘information’ is used in its everyday conception, characterized by the explanation of its semantic and epistemic properties "[…] we have additional information on the state of the gas […]". Here the amount of information ‘I’ should be properly understood as information *about* something. In this sense, the information is a resource belonging to "we" understood as epistemic agents (in this case we would speak of "observers" simply, or ”observer-scientists”) about the system referred to or observed, in this case the state of a gas. Information is directly identified with knowledge (Lombardi et al. 2016) "[…] we may happen to know […]". Here lies a context of scientific practice in which the observer understood as an epistemic agent is related to his object of study (expanding gas) by means of the informational states of the former, coded in ‘W’ complexions.

Note that the amount of information (in the ordinary-epistemic sense that we are detailing here) that an agent possesses at a particular moment about the current microstate x of the system is inversely proportional to the volume of the macrostate ‘W’ that contains x. This interpretation is usually justified by the fact that "this lack of information induces the possibility of a great variety of microscopic distinct structures, which are in practice unable to distinguish from one another" (Brillouin 1962, p. 160). That is, the greater the volume of phase in ‘W’ (the greater the number of equiprobable and indistinguishable microstates), the more difficult it will be for an observer to extract information about the current x-microstate of the physical system.

Therefore, the negative information $-\Delta$I generated during the expansion of the gas in our case would refer to how the observer’s information about the gas system decreases from the time the gas is initially represented by the tiny macrostate W_0 (the agent has a lot of information about the position/speed of the gas components, as it is confined in the tiny volume V’) until it evolves to the large phase volume macrostate W_1 (the agent now has little information-knowledge about the microscopic configuration of the gas in the huge volume V”). In conclusion, according to this epistemic interpretation of the Brillouinian concept of bound complexion-coded information, the $-\Delta$I quantity points to the loss of epistemic information by a supposed observer about the current microstate of a gas[8] during its approach to thermal equilibrium.

(B2) Complexion-encoded information (Ontic interpretation)

In the same quote, Brillouin also uses ’information’ as an intrinsic physical property of gas "the gas progressively "forgets" the information", giving the gas metaphorically the ability to ’forget’ its own information during its dynamic evolution (analogous to a system that loses kinetic energy in its evolution). Due to the underlying interconvertibility of the Negentropy Principle "Increase of entropy and loss of information proceed together", which suggests that information cannot be conceived as a resource of any epistemic agent, since it is modified only by the dynamics of the gas and not directly by the manipulation of a hypothetical agent. As will be noted, there is no need for any observer in this framework. This is, therefore, an ontic interpretation

[8] The first formulation of this idea can be traced back to G. L. Lewis’ famous dictum “Gain in entropy always means loss of information, and nothing more” (Lewis 1930; p. 577).

(information as a physical property) of the concept of complexion-encoded Brillouin's information.

From this perspective, the notion of Brillouin information expressed in complexion differences would not encode any epistemic state or information of an observer, but a physical property complementary to Boltzmann's entropy, inversely proportional to the number of microscopic configurations of the gas macroscopically indistinguishable according to a certain degree of resolution[9] or partitioning of phase space. Interestingly Brillouin introduces the now hackneyed interpretation of entropy as disorder to shed light on the ontic conception of its negentropic information "since any of these different microstructures can actually be realized at any given time, the lack of information corresponds to actual disorder in the hidden degree of freedom" (p. 160).

3 Information as entropy: Jayne's informational statistical mechanics

Another of the great currents of informational approach to thermal physics is the one developed by the American physicist Edwin T. Jaynes in his 1957 foundational double paper (Jaynes 1957a, b), with great later impact on the scientific community. Throughout his work in the second half of the twentieth century, Jaynes extended his methodological approach to virtually all areas of physics (quantum or classical, thermal or non-thermal[10]) until it became a general principle of science, as suggested in his posthumous book "*Probability Theory: The Logic of Science*" (Jaynes 2003). In his information theoretical reformulation of statistical mecanics, Jaynes starts from Shannon's theory to reconceptualize the whole theoretical edifice of statistical mechanics, conceiving it as a particular subfield of statistical inference theory. His informational approach is mainly based not on formally identifying (from their similar mathematical expressions) but on conceptually identifying Gibbs' statistical mechanical entropy, which statistically encodes the values of experimental measurement outcomes, and Shannon's IT entropy, which in turn encodes the amount of uncertainty on microstatistical data from a certain macroscopic knowledge of the system. This identification of Gibbs' and Shannon's entropy in a double-headed notion is central to his statistical mechanical approach, which is articulated around the famous 'Maximum Entropy principle' (or also 'MaxEnt', see Shenker [2020]).

Whereas the initial macroscopic parameters or constraints O_i we have of a system (for example, the values of macroscopic observables such as pressure or temperature) is insufficient to represent the microstatistical properties of the system by means of a single probability distribution, Jaynes' MaxEnt principle provides an effective algorithm to generate the least biased probability distribution ρ with respect to the agent's lack of knowledge of the microscopic properties of the observed system. According to the MaxEnt principle, the least biased probability distribution ρ with respect to our incomplete knowledge and the observed macroscopic values is precisely that which maximizes Shannon's entropy. Subsequently, this probability distribution ρ will evolve

[9] We will not enter into the debate on whether the degree of resolution implies introducing an observer-dependent element in this painting, since it does not make any substantial difference to this Brillouinian conception of information.

[10] I should thank an anonymous reviewer for noting this point.

following certain dynamic equations such as Liouville's. According to the MaxEnt proposal, at any subsequent moment t of such a dynamical evolution, the observable values O_i that can be predicted and verified experimentally will be equivalent to the mean values obtained via phase averaging (core theoretical mechanism of Gibbsian statistical mechanics) from the probability distribution ρ.

In this sense, I would argue that the Jaynesian connection between the maximization of Shannon entropy and the less biased probability distribution could be properly understood, not from a descriptive perspective, but from a normative one (in some sense revolutionary in the history of thermal physics): any rational agent should choose the probability distribution that least compromises him with the microscopic data he does not know. It would be interesting to explore carefully in future work how this MaxEnt-based norm could be epistemically justified by the enormous predictive potential it provides to the agent. This procedure (generalizable to quantum and non-thermal domains) is not only a statistically useful way of predicting-inferring quantities of thermal systems, but also reverses the methodology of traditional statistical mechanics: entropy is used to calculate distributions on microstatistical data, and not vice versa, as Shenker (2020) remarked. In fact, Jaynes himself defends his proposal not as a straightforward physical theory about thermal systems but properly as a theory of statistical mechanical predictions and inferences, where probabilities do not represent objective properties of systems (as in the case of frequentists interpretations) but epistemic states of agents, such as their lack of knowledge of macrostatistical data (Jaynes 1957a).

Our paradigmatic case of an expanding gas illustrates what is known in the literature as the 'incredibly short' Jaynesian proof of the Second Law (Sklar 1993; Parker 2011), whose validity won't be assessed here. First, from the measured values of certain observable macroscopic properties O_i (e.g. temperature or pressure) of the gas at the initial moment t_0 we define a probability distribution ρ that maximizes its Shannon entropy H[ρ] as a function of our macroscopic knowledge encoded via O_i. Once the gas begins to dynamically evolve by expanding in the vessel, we measure again the value of the observable property O_i at time t, on which we redefine a new probability distribution ρ* that maximizes Shannon entropy. According to Jaynes (1957b), the fact that $S[\rho(t_0)] \leq S[\rho^*(t)]$ shows how Gibbs entropy increases as the gas approaches equilibrium via free expansion (then, the uncertainty encoded via Shannon entropic quantities similarly increases until the system reaches its equilibrium state), according to the Second Law as interpreted in statistical terms.

(J1) Probability distributions-encoded information (Epistemic interpretation)

Indeed, as we have just seen, the notion of information used in Jaynes' statistical mechanical formalism is explicitly Shannon's entropy measure, conceptually identified as Shannon–Gibbs in his formalism. This celebrated quantity is usually defined and interpreted in many ways regardless of the theoretical scope, although a simple way of understanding its functioning in the context of statistical mechanics is as the degree of unexpectedness or unpredictability generated by a set of symbols m as a function of the probability distribution ρ over the symbol alphabet 'Λ'. Frigg (2004) offers a technically robust epistemic interpretation of Shannon entropy as a measure of the degree of unpredictability[11] of the dynamic evolution of a physical system (say a gas), represented in how scattered is the form of probability distribution ρ over the phase space Γ of the observed system and interpreting each symbol as a phase space cell of partition α.

Note that within Jaynes' MaxEnt framework another concept of information emerges implicitly from the epistemic interpretation of the probabilities used to statistically model the dynamical properties of the microscopic components of the system. Its connection with Shannon's measure is a matter that needs to be calmly addressed in another paper. Such a conception is none other than the everyday (and semantic-epistemic, as we remarked in Sect. 3) notion of information applied to the highly technical context of statistical mechanical probabilities. In this sense, a probability distribution ρ would somehow encode both the prior (semantic-epistemic) information or knowledge of an agent about the macroscopic parameters O_i and its degree of uncertainty on the microscopic properties of the system.

This would be directly applied in our paradigmatic case of the expanding gas, where the MaxEnt-generated distribution ρ properly represents the least biased probability distribution encoding the observer's initial epistemic information about the volume, pressure or temperature (O_i) of the gas at t_0. After letting the probability distribution ρ to evolve according to the (Liouvillean) dynamics of the system, the observer's lack of epistemic information about microstatistical data are distributed regarding O_i would be inferentially exploited to predict future values of these observable properties O_i. According to the MaxEnt principle, the phase averages values derived from the least biased (given our incomplete knowledge) distribution ρ at *t* that maximizes our Shannon-entropy-encoded uncertainty about the microscopic properties of the system will straightforwardly correspond to the values of the observable quantities O_i that we can predict at *t*. Therefore, according to Jaynes informational MaxEnt proposal, by fitting the (micro)statistical description of the system to our maximum degree of Shannon-coded uncertainty about microstatistical information we are properly maximizing the epistemic capacity of the agent-observer to predict the observable values that the system will take in its evolution.

4 Assessing the explanatory power of informational approaches

Summarizing, we have just presented the three main families of informational treatments (each one nurtured from on different concepts, interpretations and technical resources) of one (if not 'the') thermal behavior*par excellence*: the approach to the state of thermal equilibrium of an ideal gas by means of a free expansion process. At this point we can defend that these three informational approaches, namely B1, B2 and J1,[12] constitute the historical-conceptual root on which all the proposals developed up

[11] Specifically, Frigg (2004) establishes a robust connection between Kolmogorov–Sinai metric entropy and Shannon entropy, and on this basis proposes an interpretation of the latter concept as 'degree of unpredictability'.

[12] From now on we will use B1, B2 and J1 to refer to the tracings of Brillouin's equilibrium approach in its epistemic (B1) and ontological (B2) and Jaynes' (J1) formulation, respectively, exposed in Sect. 4.

to the present[13] will be built. One of the most illustrative examples of this thesis was recently put forward by Neo-Jaynesian physicist Arieh Ben-Naim (2008), one of the most active informationalists nowadays, who defends a reformulation of entropy as lack of epistemic information (Brillouinian) together with an epistemic interpretation of this statistical measure and a strong identification between Shannon's information and entropy (Jaynesian): “The fact is that there is not only an analogy between entropy and information, but an identity between the thermodynamic entropy and Shannon's measure of information” (Ben-Naim 2008, p. 22).

Up to this point, we might ask, in what sense can informational approaches to thermal physics provide a robust explanation of the thermal behavior of physical systems from the dynamical behavior of their components? Preliminarily, we assume in the vein of Frigg and Werndl[14] (2011b) that any robust explanation[15] of this phenomenon would consist of an ‘explanandum’ that depends constitutively on regularities or causal structures connected with ontic-dynamical (not quantum but classical, in our case) properties of the physical components of the target system. Then, to answer the above question we will separate the elements of the information frameworks that can contribute to such a robust explanation into (i) interpretative, (ii) conceptual, and (iii) technical-formal, although these are inextricably interwoven in Brillouin's and Jaynes' proposals.

4.1 Evaluating the explanatory import of B1 (Epistemic negentropic information)

We first encounter the epistemic formulation of Brillouin's notion of negentropic-information B1, as outlined in Sect. 3, and immediately proceed to unpack its interpretative, conceptual and formal contributions to develop a robust explanation of the thermal process of gas equilibrium. It should be noted initially that it is not possible to derive an explanation of this thermal phenomenon from B1 without appealing to an interpretation of Boltzmann's complexions from the everyday notion of ‘information’, which is inseparable from semantic-epistemic properties. This was already pointed out

[13] Of course, the justification of this thesis requires a thorough historical analysis, which we leave for a future work.

[14] Frigg and Werndl (2011b) developed a robust explanation (in the sense detailed above) of the approach to equilibrium in Boltzmann's original line. They based themselves on -ergodicity, a property that states that a certain system is ergodic except in a region of the phase space, which would explain the tendency to thermal equilibrium of a certain gas from the real dynamics of its components. In spite of its robustness, such explanation is limited to extremely idealized mathematical models of gases.

[15] Following Frigg and Werndl (2011b), in this paper we do not commit ourselves to any particular model of explanation (see Batterman 2002, Chapter 3), although we demand minimally that any suitable candidate must appeal directly to objective facts about the actual distribution of microstates in the phase space of the target system. Nevertheless, it should be remarked that here we are not begging the question against the information-theoretical approaches. This minimalist criterion of what an explanation in SM should consist of allows that from any plausible statistical mechanical approach, including the informational one (this is the key), one could somehow give satisfactory explanations of the equilibrium approach, as long as they directly appeal to these objective facts. Illustratively, this is the case of David Wallace, who from an enhanced Gibbsian framework (the so-called ‘Zwanzig–Zeh–Wallace’ framework) tries to explain this type of thermal behavior by appealing to the objective facts of the microstatistical dynamics statistically encoded in the evolution of the probability distribution (see Robertson 2020).

by Earman and Norton (1999) in their review of the informational approaches to the complex thermal phenomenon of Maxwell's demon:

> Brillouin's labeling of the quantity in [(4)] as 'information' is intended, of course, to suggest our everyday notion of information as knowledge of a system. But those anthropomorphic connotations play no role in the explanation of the Demon's failure. All that matters for the explanation is that the quantity I is an oddly labelled quantity of entropy and such quantities of entropy are governed by the Second Law of thermodynamics. The anthropomorphic connotations of human knowledge play no further role" (Earman and Norton 1999 , p. 8).

In this sense, what does the everyday notion of information contribute to the alleged explanation? Our diagnosis cannot be different from the one shown in the above quotation by Earman and Norton for the problem of the Maxwellian devil: the fact that the complexion-coded information of an observer about the current microscopic configuration of the gas decreases as it approaches equilibrium (while the number of microstates increases logarithmically until it reaches the phase region corresponding to equilibrium) does not illuminate, and even less satisfactorily explains why a gas can reach its thermal equilibrium by expanding from a corner of a vessel until it is evenly distributed throughout the vessel. At best, this decrease in information would pedagogically help to understand (although conceptually inaccurate) the BSM approach to equilibrium, as Denbigh and Denbigh (1985, p. 117) argued: "notions about 'loss of information' can sometime be useful. But they […] can also give rise to mistakes".

There is also no conceptual support that allows an explanatory connection between B1 and the thermal phenomenon of equilibrium. In contrast to the quantum domain, where (regardless of the interpretation we subscribe to) there is a certain consensus within the scientific community about the physically objective influence between the observer and the observed system, in the classical domain in which we find ourselves there is no physically relevant connection between the epistemic states of the observers and the objective properties of the observed systems. Therefore, assuming the lack of causal objective connection between observer states (informationally interpreted) and states of the observed systems, any explanation for such a connection will be a physically irrelevant explanation. At most, B1 will be able to explain with difficulty how the informational states of the observers work given a Boltzmannian description, but this remains a physically (and probably also 'psychologically') insignificant explanation with respect to the thermal phenomenon that concerns us here.

Finally, we find no formal or technical contribution of Brillouin's proposed negentropic information to the explanation of the thermal equilibrium phenomenon. Our main argument refers to K. G. Denbigh (quoted with his partner above), one of the major critics of the informationalist approach in thermal physics during the second half of the twentieth century, who pointed out that the concept of "bound information is nothing more than a name given by Brillouin to an "entropy change" encoded in Boltzmann-type complexions" (Denbigh 1981). Of course, this thesis is valid for both the ontological and the epistemic interpretation of Brillouin's proposal. In this case, the idea is not only that the measure of 'bound information' (quantity that is supposed to be physically relevant) does not refer to anything that Boltzmann's entropy does not do, even if these informational states are within the observers, but also that the thesis of information-negentropy interconvertibility is defended as a mere triviality that does not contribute anything substantial either to the thermophysical practice or to the explanation of the process of equilibration.

4.2 Evaluating the explanatory import of B2 (Ontic negentropic information)

As for the ontic interpretation of Brillouin's informational proposal (B2), the recipe we will follow is identical to the epistemic version: to delve into the factors that may contribute to a robust explanation of our paradigmatic thermal process. There is no doubt that, as specified in Sect. 3, the most decisive interpretative factor in (B2) is to assume that the measure of Boltzmannian entropy quantifies in some way (of course, not specified by Brillouin) the level of "disorder" in the microscopic configuration of the physical systems under consideration. This serves him to encode what he calls 'bound information' not in the states of the observer (as in the epistemic version), but in the degrees of freedom of the physical system under consideration. Of course, this interpretation is not only theoretically-conceptually incorrect, but also lends itself enormously to confusion: what kind of disorder are we talking about? disorder in space, disintegration of components? For example, in the adiabatic demagnetization of a gas, its components will be highly "ordered" (aligned with the same spin) in a state of high entropy, while they will be "disordered" (with arbitrary spin) in a state of low entropy. Therefore, capitalizing on the interpretation of entropy as disorder on the Brillouin (B2) information apparatus can only generate highly confusing explanations.

On the other hand, by treating the quantitative concept of information as a quantity of physical character within the ontic framework (B2), we position ourselves with respect to what the philosopher of physics Floridi (2011, p. 90) calls 'Wiener's problem' which deals with the ontological character of information. By treating sets of microscopic 'W' configurations of physical systems literally as information carriers (information *about* themselves, let us not forget), we can fall into the risk of talking about information flow during the dynamic evolution of these systems, represented as transitions between 'W_S'. As the history of recent physics has shown, the increasing proliferation of information perspectives in various fields encouraged the metaphor of 'information flow' to be taken in a literal sense even within the scientific community: "information is flowing, moving from place to place" (Seife 2007, p. 3). According to Timpson (2013), we are making a categorical error here by assuming the concrete-physical character of an abstract entity such as information. There is something like a 'flow of information' that decreases as the gas approaches equilibrium, and therefore no explanatory connection between the two. Other authors such as Lombardi et al. (2016, p. 2002) also argue that since quantitative concepts of information are neutral with respect to physical theories, they cannot have physical nature regardless of the particular medium on which it is implemented. Finally, Floridi (2011, p. 90) directly defends the ontological neutrality of information, which makes it impossible to ontologically characterize it physically or not. Therefore, any plausible explanation of thermal phenomena based on any non-empirically justified form of ontological inflationism regarding information will constitute a conceptually inconsistent explanation, which could result in (i) the categorical error of reifying the information, (ii) confusion between the nature of the information and its implementation support, or (iii) the denial of its ontological neutrality.

Here we would also consider Denbigh's triviality argument (Sect. 5.2) regarding the formal contribution of the information apparatus (B2) to thermal explanations. Although in this context the convertibility thesis under the Negentropy Principle implies that the physical quantities of information linked 'I' can be transformed into quantities of negative entropy '-S' (in analogy to how one type of energy can be transformed into another), in fact, such a transformation is completely trivial, while the physical quantities are already by definition differences of Boltzmann entropy. Although they bear two different names, there are not two different properties which are physically significant, but only one. I defend in this point that the Brillouinian informational measure does not imply any technical or theoretical addition to the statistical mechanical entropy notion already existing in real scientific practice: to say that information decreases in the approximation to the equilibrium of a gas is trivially equivalent to saying that entropy. Therefore, an explanation along these lines would not only be explanatory and redundant with respect to another possible explanation that can be offered from BSM, but would also incorporate the conceptual deficiencies and interpretative inconsistencies outlined above.

4.3 Evaluating the explanatory import of J1 (epistemic probabilistic information)

With (J1) we not only change the informational proposal, but also properly move to the wide theoretical context of GSM,[16] which is basic in terms of the explanatory power as we will defend in the following section. It should be noted initially that Jaynes himself (1957a; b) developed the MaxEnt principle as an apparatus whose essential epistemic value was its effective predictive capacity, and not the straightforward explanation of thermal phenomena from the physical behavior of their components: "in the problem of prediction, the maximization of entropy is not an application of a law of physics, but merely a method of reasoning" (Jaynes 1957a, p. 630) However, it was precisely the later Jaynesian authors who precisely claimed the epistemic potential of MaxEnt formalism concerning physical phenomena, as we clearly see in the recent case of Parker: "the Jaynesian offers an explanation of the content of the second law [and the approach to equilibrium], in that it explains the impossibility of exploiting the statistical nature of thermal systems to generate work at no entropic cost." (Parker 2011, p. 855).

For Jaynes MaxEnt-based statistical mechanical apparatus, its interpretative tools (mainly, its epistemic interpretation of probabilities, Shannon and Gibbs entropy) are central to understanding its explanatory contribution to the field of non-equilibrium thermal physics. In this sense, it should be noted that Shannon's entropy also acquires epistemic power here insofar as it is based on a probability distribution, although in itself it does not have evident epistemic properties like the everyday notion of

[16] Note that the use of Gibbs entropy and the exploitation of Shannon's formal-theoretical apparatus is a key difference with Brillouin's informational proposal, while "Jaynes works in the framework of the Gibbsian approach to statistical mechanics, in which entropy is associated with a function over the entire state space, rather than the measure of a measure of a microstate" (Shenker 2020, p. 21).

information. The most widespread way to provide epistemic content to Shannon's entropy is to interpret it as a measure of the degree of epistemic uncertainty encoded by a probability distribution, although these two epistemically-flavored measures might well be conceptually different,[17] following Timpson: uncertainty and Shannon entropy only (conceptually) coincide in the extremely remote scenario in which "none of the standard features involving what one learn, or that one might infer (…) are in play" (Timpson 2013, p. 30).

Nevertheless, Shannon's measure not only acquires epistemic content within MaxEnt formalism through the epistemic interpretation of probabilities, but also from the overall (mainly epistemic) reconceptualization of statistical mechanics as a theory not about physical systems but properly about statistical mechanical prediction and inferential techniques. In this sense, Shannon entropy would somehow encode the degree of lack of information of an agent about the microstadistic properties of the system, whose maximization allows the construction of the least biased probability distribution ρ^* maximizing the capability of an agent to statistically predict the observable values the target system (see Sect. 4). Thus, the fundamental Jaynesian justification for the choice of Shannon's information measure over others (e.g. Hartley or Fisher) is strictly epistemic, because of its key role in the conceptual connection with Gibb's entropy measure and the epistemic interpretation of probabilities and the entire statistical mechanics.

Up to this point, we should ask about how could this strongly informational-epistemic proposal of Jaynes give a satisfactory explanation of the equilibration process of thermal systems. Here we can retrieve this famous quotation from David Albert:

> Can anybody seriously think that it is somehow necessary, that it is somehow a priori , that the particles that make up the material world must arrange themselves in accord with what we know, with what we happen to have looked into? Can anybody seriously think that our merely being ignorant of the exact microconditions of thermodynamic systems plays some part in bringing it about, in making it the case, that (say) milk dissolves in coffee? (Albert 2000 , pp. 64–65).

This criticism, originally conceived for GSM, finds a natural application in Jaynes MaxEnt proposal. In an analogous way to what we also find in B1, Albert criticizes the strategy of explaining the physical states of a thermal system, e.g. the approximation to the thermal equilibrium of milk in coffee, just by appealing to an observer's epistemic states, as his lack of knowledge regarding the microscopic configuration of the gas. Since we ruled out (see Sect. 5) the possibility of explaining physical phenomena through the causal intervention of the epistemic states of the agents, we should now ask ourselves in what sense the MaxEnt formalism provides an explanation to the equilibration process of systems with thermal behavior. Thus, the central question here would be: Does Jaynes MaxEnt principle explain the approach to equilibrium of a physical system by providing us with the least biased probability distribution (via maximizing Shannon's entropy)? Our answer to this question is negative for three main reasons.

[17] "The roles of H(X) as a measure of uncertainty and a measure of Shannon information are logically distinct, thus the concept of the quantitative Shannon information is not the same concept as the concept of measure of uncertainty" (Timpson 2013, p. 26).

First, while Jaynes' formalism does not delimit any explanatory causal mechanism or structure in thermal systems that satisfactorily account for their approximation to equilibrium (mainly because their theoretical functioning does not depend at all on the actual dynamics of the system), its explanatory power would be then limited to the realm of inferential technics and predictive procedures. For example, the MaxEnt principle could actually explain why we should start from a probability distribution ρ^* that maximizes Shannon entropy: namely, because such a distribution will be the least biased probability distribution compatible with our macrostatistical knowledge and our microstatistical uncertainty. However, it would be difficult to rationally justify the belief that our reasons for choosing one particular probability distribution over another[18] merely from the fact that it maximizes the value of Shannon's measure of our microstatistical uncertainty could somehow explanatorily account for objective facts underlying a thermal system:

> There's something completely insane (if you think about it) about the sort of explanation we have been imagining here. (…) Suppose that there were some unique and natural and well-defined way of expressing, by means of a distribution-function, the fact that "nothing in our epistemic situation favors any particular one of the microconditions compatible with X over any other particular one of them" Can anybody seriously think that that would somehow explain the fact that the actual microscopic conditions of actual thermodynamic systems are statistically distributed in the way that they are? (Albert 2000 , p. 64).

The second reason why the MaxEnt principle could not satisfactorily explain the approach of physical systems to equilibrium is the same as the Neo-Boltzmannians (Callender 1999; Albert 2000) developed to the explanations derived from GSM. Namely, that the MaxEnt does not straightforwardly refer to actual physical systems but to the epistemic-rational capacity of agents to assign probability values to microstates of the system according to their degree of uncertainty about which is the actual microstate of the system. In this sense, this proposal has to be technically based on probability-based ensembles to conceptually identify Gibbs' entropy and Shannon's measure. Nevertheless, in the case of Jaynes, these statistical ensembles do not represent fictitious collections of physical systems (à la Gibbs [1902]) but properly the degrees of microscopic uncertainty of the agents concerning the microstatistical properties of the target system (Jaynes 1957a). In fact, as Frigg and Werndl (2011a) point out, the Gibbs coarse-grained entropy of an ensemble on which a plausible MaxEnt-based explanation would be based only coincides numerically with both (empirically significant) thermodynamic entropy and Shannon's measure in extremely idealized cases, such as in the modeling of ideal gases already in thermal equilibrium via microcanonical ensembles. However, during an equilibration process not only is thermodynamic entropy not conceptually identical to Shannon entropy (against what

[18] Although the Boltzmannian and Gibbsian frameworks also suffer from this problem, there are factors directly linked to the microstatistical dynamics of the system which are theoretically relevant for their choice of probability measure, unlike informational (i.e. Jaynesian) approaches. For example, the particular choice of the Lebesgue's probability measure in both the Boltzmann and Gibbs frameworks is usually justified by its conventional-pragmatic advantages in terms of its conservation during the evolution of the system according to Liouville's theorem (Shenker 2020).

the Neo-Jaynesian Ben-Naim [2008, p. 22] defended at the beginning of this chapter), but even the values of Gibbs' and Clausius entropy will not necessarily coincide. As (the also Neo-Jaynesian) Parker recognized: "it [a Jaynesian explanation] does not claim to make direct contact with the thermodynamic entropy as it is usually conceived in thermodynamics, this is an inevitable feature of such interpretations" (Parker 2011, p. 855).

The last but not least reason lies in the use of coarse graining and phase averages as theoretical-technical elements (inherited from GSM formalism) belonging to any MaxEnt-based plausible explanation of the thermal phenomenon that concerns us here, procedures explicitly defended by neo-Jaynesians such as Ben-Naim (2008) or Parker (2011). On the one hand, Jaynesian coarse-graining procedure is based on the partitioning of phase space according to macroscopic constraints or observable properties Oi, which depends on contingent factors such as the instrumental capacity of the agents (see Uffink 2007; Frigg 2008). On the other hand, and following Frigg and Werndl (forthcoming), phase averaging constitutes only a mere computational shortcut for calculating observable quantities, whose physical significance is debatable. Therefore, any MaxEnt explanation will be based on contingent technical elements and of mere computational value, and therefore will not be thermophysically significant in a strong sense.

One could ask at this point in our argumentation: if MaxEnt cannot robustly explain the equilibrium approach for the reasons outlined above, then could the practical success that this approach has brought to the scientific community during its more than seven decades of life suggest to us that the MaxEnt may implicitly contain a robust explanatory mechanism at the ontological level? Firstly, the MaxEnt principle has enjoyed enormous applicability since the late 1950s in various scientific fields, from ecology to cosmology (see Kleidon and Lorenz 2005); however prestigious physicists such as Balescu (1997) argue that, despite its extensive applicability, MaxEnt formalism has so far failed to achieve any substantial results in the empirical sciences. Even if we concede its practical success, the issue of whether the MaxEnt is implicitly based on ontological mechanisms of thermophysical systems that can be explanatorily exploited is properly metaphysical as well as closely related to our realistic or unrealistic attitude towards the content of a particular theory.

However, our straightforward interest in this paper is to analyze whether Jaynes' theoretical proposal has explicit formal-conceptual resources that directly explain the thermal phenomenon that concerns us here, and based on the arguments detailed above we now argue that any plausible MaxEnt-based explanation of the thermal equilibrium approach of individual gas system derived from J1 will be interpretatively incoherent (since epistemic states cannot causally intervene or properly explain physical states), conceptually inconsistent (ensembles do not refer to physical properties of individual systems) and thermophysically insignificant (mainly because of the use of coarse-graining and phase averages).

5 Informational thermal physics as epistemic parasite

In the previous section we have analyzed the capacity of Brillouin's (both in its epistemic and ontic aspects) and Jaynes' informational proposal to explain the approach of a gas to equilibrium, concluding that neither can offer robust and physically significant explanations of this phenomenon due to various interpretative inconsistencies, conceptual inconsistencies and formal incorrectness. At this point we will argue that any possibility of explaining thermal phenomena on the basis of their microscopic constitution from an informational perspective depends fundamentally on the constitutive relationship between Brillouin's approach and the MaxEnt formalisms with BSM and GSM, respectively, where the formers are presented as 'epistemic parasites' of the latter. The term 'parasite' here is not intended to be pejorative, it simply highlights how certain theoretical proposals (such as those of Brillouin and Jaynes) draw on conceptual and technical resources from other proposals (that of Boltzmann and Gibbs) for their epistemic benefit.

First, Brillouinism, both in its formulation B1 and B2, stands on the theoretical foundations of BSM: it is assumed that phase space Γ is partitioned into non-overlapping regions whose microstates are equiprobable, the probability being defined as proportional to the measurement of the phase volume of macrostates, and so on. As we assessed in Sects. 5.1 and 5.2, any factor (interpretative, conceptual or technical-formal) surrounding the Negentropy Principle that can contribute to develop a physically meaningful explanation lies in exploiting the geometry of phase space, which is the core of the Boltzmannian approach. Let us remember once again that his concept of 'bounded information' is nothing more than differences between dynamically accessible volumes of phase. While the idiosyncratic explanatory elements of Brillouinism (use of the ordinary notion of 'information', interpretation of entropy as disorder, interconvertibility between information and negative entropy, and so on) are presented as interpretatively inconsistent and conceptually inconsistent, the only way to develop satisfactory physical explanations is to rely on the theoretical resources of BSM (Sect. 2.1). We can therefore conclude that Brillouin's informational perspective does not add any explanatory advantage to Boltzmann's statistical mechanics with respect to the thermal equilibrium approach. Not only is the former theoretically based on the latter, but it also takes advantage of its epistemic resources.

Secondly, any plausible Jaynesian MaxEnt-based explanation (J1) of the thermal process of a gas approaching equilibrium would be intrinsically dependent on the technical-theoretical resources constituting GSM: (i) probability distributions are used to represent the statistical properties of fictitious collections (assemblages) of systems, but in no case do they directly appeal to dynamic causal structures to explain the phenomenon; (ii) coarse-graining and phase-averaging are also used as purely computational resources (Sklar 1993; Frigg 2008) to give a statistical mechanical explanation of a thermophysical phenomenon. Of course, this does not mean that Jaynes' MaxEnt methodology depends constitutively on GSM methodology, since as we pointed out in Sect. 4, the MaxEnt algorithm reverses the methodological procedure of traditional or BSM/GSM statistical mechanics: illustratively, while entropy is a primitive concept for the MaxEnt principle, for BSM and GSM entropy is a concept that should be derived from the equations of motion and certain additional dynamical-statistical hypotheses

(Shenker 2020, p. 22). As long as the methodological structure is reversed, we cannot satisfactorily justify the choice of the probability measure of BSM or GSM by the interpretative, conceptual or technical-theoretical resources of Jaynes' framework.[19] For instance, it would not make sense to justify the choice of a distribution probability from GSM because it is the least biased (via maximizing Shannon entropy), but because it has been derived from the canonical ensemble that best describes through the NVT variables a physical system that exchanges energy with a reservoir. On the other hand, the properly idiosyncratic resources of the MaxEnt, fundamentally (a) its strongly epistemic interpretation of probabilities and entropy measures, (b) its conceptual identity of Gibbs (and Clausius) entropy and Shannon entropy and (c) its pragmatically useful but physically meaningless procedures, have been shown to be interpretatively inconsistent, conceptually inconsistent and technically-theoretically imprecise (Sect. 5.3). Therefore, any plausible MaxEnt-based explanation of gas equilibrium will intrinsically depend at the end of the day on certain technical and conceptual resources of Gibbsian statistical mechanics (Sect. 2.1) to elaborate an explanation of this phenomenon; it is in this precise sense that Jaynes' informational proposal epistemically parasitizes GSM.

It should be noticed that our argument presented here does not depend at all on BSM being explanatory superior to GSM, as Neo-Boltzmannian authors such as Callender (1999) or Albert (2000) argued. The fundamental thesis we defend is that the informational treatments of Brillouin and Jaynes of a gas reaching thermal equilibrium do not add any additional explanatory value to the statistical mechanical accounts of Boltzmann and Gibbs, respectively. On the contrary, since the interpretative, conceptual and formal-technical resources from B1, B2 and J1 (e.g. epistemic interpretations of probabilities and entropies, or identification of entropic measurements and information concepts) could only provide what Batterman (2002) calls 'epistemic noise[20]' to a plausible explanation, Brillouin and Jaynes' informational proposal must then parasitize conceptual and technical resources from other theoretical apparatuses such as BSM and GSM.

For example, when Brillouin uses the expression "we may say that the gas progressively "forgets" the information" (Sect. 3) with explanatory force, the only way in which this constitutes a satisfactory explanation[21] depends on it actually referring to how the phase path describing the evolution of the system transits through progressively more volumetric phase regions. Appealing to the 'gas forgetting information' only adds to the interpretative incoherence of employing the ordinary notion of information, the conceptual inconsistency of objectifying information, and the trivial substitution of 'negative entropy' for 'information', where all these ingredients are sources of epistemic noise. On the other hand, when neo-Jaynesian authors such as Parker state that "if knowledge is somehow lost (…) then the phase volume [of the probability distribution] might conceivably increase" (Parker 2011, footnote 11),

[19] I am grateful to an anonymous reviewer for suggesting that I should clarify this issue.

[20] Batterman (2002) uses the term 'epistemic noise' to refer to those conceptual or technical elements of a model that do not contribute positively to the explanation of a physical phenomenon.

[21] Whether this explanation is not only satisfactory, but also 'robust' depends on questions related to the conceptual foundations of statistical mechanics and how its model-descriptions manage to have empirical thermodynamic content (Callender 1999).

the epistemic interpretation of the mechanical-statistical MaxEnt formalism does not contribute explanatorily to account for the physical facts underlying the approach to equilibrium, as in the case of a gas free expansion in a vessel. This epistemic interpretation constitutes mere epistemic noise within plausible explanations, such as the one that can be given from the epistemic parasitism of the Gibbsian coarse-graining, namely, that the entropy of an ensemble will increase because we decrease our resolution capacity.

6 Conclusion

In this paper we have defended the thesis that the informational treatments of certain thermal behaviors (in our case, the approximation of a gas to the state of thermal equilibrium) do not import any robust explanatory burden additional to that of statistical mechanics, against a growing number of authors currently defending (Seife 2006; Ben-Naim, 2008). Before concluding, it should be noted that what is known as 'information physics' (Bais and Farmer 2007), which is devoted to the application of informational concepts and techniques in physics, is now an active field covering almost all the fundamental areas of physics today: from black hole thermodynamics (where the influence of Brillouin and Jaynes was decisive in Bekenstein, see Wüthrich [2017]) to quantum information theory, or the information theoretical foundation of quantum mechanics (Bub 2005).

As we have seen, these informational approaches in the particular domain of thermal physics can be strategically divided into two large groups,[22] namely those that assume that the concepts of information are complementary (Brillouinism) and those that assume an identity between the concepts of information and entropy (Jaynesianism). After evaluating the interpretative, conceptual and formal factors of the informational framework of Brillouin (1962), both in its ontological and epistemic version, and that of Jaynes (1957a) contributing to the generation of explanations of this particular thermal phenomenon, we have concluded that due to its various interpretative inconsistencies, conceptual inconsistencies and technical-formal deficiencies it cannot be possible to derive a robust and thermophysically significant explanation of the approach to equilibrium of a gas from such informational approaches. This conclusion in no way seeks to detract from the vast intellectual work of Brillouin and Jaynes, in many ways unjustly forgotten within the philosophical literature, but rather to maintain a modest critical attitude towards the later generalized misuse of their proposals: "Brillouin concluded that thermodynamic entropy and Shannon entropy were directly related. You could use the language of information theory to analyze the behavior of a box full of gas." (Seife 2007, p. 79). Therefore, our focus has not been so much Jaynes as the misuse of the MaxEnt principle in thermophysical explanations by Neo-Jaynesians

[22] This historiographic proposal to classify the informationalist trends in thermophysics in two major groups is parallel to the suggestion of Parker (2011), who defends the existence of two main currents: namely, Jaynesianism and Landauerianism. The latter, which is essentially based on the evaluation of the physical costs of information processes, is based on the ideas of Rolf Landauer, PhD student and intellectual disciple of Brillouin at MIT. Since it would be possible to satisfactorily understand Landauerianism as a proper specialization of Brillouianism (a thesis whose defense we leave for a later paper), our classification generalizes the one offered by Parker.

such as Parker (2011) (Sects. 5.3 and 6) or Ben-Naim (2008) (Sect. 5) among other illustrative cases; and likewise, in the case of Brillouin.

The results of our critical analysis generate a constructive skepticism about the prospects of these two broad informational frameworks to explanatory account for more complex thermal phenomena in non-equilibrium thermophysics, or even in other sub-fields of this discipline. Here we have defended that, among the many epistemic virtues of the two groups of information proposal analyzed (where, for example, the MaxEnt principle has shown to have an enormous predictive power in various fields of application (Kleidon and Lorenz 2005)]) cannot be properly found their capacity to robustly explain the thermal phenomenon of equilibrium of a gas from the properties of its molecular components. Moreover, it has been specifically argued that the explanatory power of informational approaches to thermal physics intrinsically exclusively depends on epistemically exploiting, after a dense layer of reinterpretation and reconceptualization, the technical-theoretical resources of Boltzmann statistical mechanics (in the case of Brillouinism) and Gibbsian (in the case of Jaynesianism), as long as their own idiosyncratic elements (e.g. epistemic interpretation of probability-entropy, conceptual identification of entropy-information) only provide ‘explanatory noise’ (Batterman 2002). This is precisely what we have called ’epistemic parasitism’ in Sect. 6.

Nevertheless, this should not at all be a tragedy for the current Jaynesian agenda if we consider it, not as a properly descriptive-explicative theory (as it has sought to exploit in recent decades), but as a normative-predictive proposal in the original vein of Jaynes (1957a) himself (see Sect. 4). Our general aim in this paper has been to vindicate a healthy skepticism against the radical optimism of many informationalists in thermal physics, as shown by bold statements such as “the information-theory treatment of thermodynamics clarifies the concept of equilibrium” (Tribus and McIrvine 1971, p. 186). In short, we have just tried to contribute modestly with our critical analysis to encourage a minimum of critical attitude towards the actual epistemic value of certain major trends in current scientific thought, as in the case of informational physics, with an increasing presence within our leading scientific communities.

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