Observation of the Final Boundary Condition: Extragalactic Background Radiation and the Time Symmetry of the Universe*

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Abstract

This paper examines an observable consequence for the diffuse extragalactic background radiation (EGBR) of the hypothesis that if closed, our universe possesses time symmetric boundary conditions. By reason of theoretical and observational clarity, attention is focused on optical wavelengths. The universe is modeled as closed Friedmann-Robertson-Walker. It is shown that, over a wide range of frequencies, electromagnetic radiation can propagate largely unabsorbed from the present epoch into the recollapsing phase, confirming and demonstrating the generality of results of Davies and Twamley [1]. As a consequence, time symmetric boundary conditions imply that the optical EGBR is at least twice that due to the galaxies on our past light cone, and possibly considerably more. It is therefore possible to test *experimentally* the notion that if our universe is closed, it may be in a certain sense time symmetric. The lower bound on the "excess" EGBR in a time symmetric universe is consistent with present observations. Nevertheless, better observations and modeling may soon rule it out entirely. In addition, many physical complications arise in attempting to reconcile a transparent future light cone with time symmetric boundary conditions, thereby providing further arguments against the possibility that our universe is time symmetric. This is therefore a demonstration by example that physics today can be sensitive to the presence of a boundary condition in the arbitrarily distant future.

1 Introduction

Quantum cosmology studies the relation between the observed universe and its boundary conditions in the hope that a natural *theory* of the boundary condition might emerge (see [2] for an outstanding review of this enterprise.) Assessment of a particular theory requires an understanding of its implications for the present day. To that end, this paper elaborates on work of Gell-Mann and Hartle [3] and Davies and Twamley [1] by examining the observable consequences for the diffuse extragalactic background radiation (EGBR) of one possible class of boundary conditions, those that are imposed time symmetrically at the beginning and end of a closed universe [3], and sketches some of the considerable difficulties in rendering this kind of model credible. Assuming such difficulties do not vitiate the consistency of time symmetric boundary conditions as a description of our universe, the principal conclusion is that these boundary conditions imply that the bath of diffuse optical radiation from extragalactic sources be at least twice that due only to the galaxies to our past, and possibly much more. In this sense, observations of the EGBR are observations of the final boundary condition. This conclusion will be seen to follow (section 3.A) because radiation from the present epoch can propagate largely unabsorbed until the universe begins to recollapse ([1], and section 2), even if the lifetime of the universe is very great. By time symmetry, light correlated

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with the thermodynamically reversed galaxies of the recollapsing phase must exist at the present epoch. The *minimal* predicted "excess" EGBR in a universe with time symmetric boundary conditions turns out to be consistent with present observations (section 3.C), but improved observations and modeling of galactic evolution will soon constrain this minimal prediction very tightly. In addition, many physical complications with the ansatz that time symmetric boundary conditions provide a reasonable and consistent description of the observed universe will become apparent. Thus this work may be viewed as outlining some reasons why even if very long-lived, our universe is probably not time symmetric.

The plan of the paper is as follows. Section 1.A discusses a model universe that will define the terms of the investigation. Section 1.B provides some perspective on doing physics with boundary conditions at two times with an eye toward section 4, where some aspects of the reasonableness of two time boundary conditions not immediately related to the extragalactic background radiation are discussed. Section 2 generalizes and confirms work of Davies and Twamley [1] in showing that for processes of practical interest, our future light cone (FLC) is transparent all the way to the recollapsing era over a wide range of frequencies, even if the universe is arbitrarily long-lived. Section 3.A explains why this fact implies a contribution to the optical extragalactic background radiation in a universe with time symmetric boundary conditions in excess of that expected without time symmetry. In the course of this explanation, some rather serious difficulties will emerge in the attempt to reconcile time symmetric boundary conditions, and a transparent future light cone, into a consistent model of the universe which resembles the one in which we live. Section 3.C compares the predictions of section 3.A for the optical EGBR to models of the extragalactic background light and observations of it. Section 5 is reserved for summation and conclusions.

1.A Motivations and A Model

The possibility that the universe may be time symmetric has been raised by a number of authors [4, 5, 6, 7, 8, 9, 10, 11]. Of course, what is meant is not *exact* time symmetry, in the sense that a long time from now there will be another Earth where everything happens backwards. Rather, the idea is that the various observed "arrows of time" are directly correlated with the expansion of the universe, consequently reversing themselves during a recontracting phase if the universe is closed. Of central interest is the thermodynamic arrow of entropy increase, from which other time arrows, such as the psychological arrow of perceived time or the arrow defined by the retardation of radiation, are thought to flow [12, 9, 13, are some reviews]. However, the mere reversal of the universal expansion is insufficient to reverse the direction in which entropy increases [14, 12, 5, 6, 15, 16, 17, 18]. In order to construct a quantum physics for matter in a recollapsing universe in which the thermodynamic arrow naturally reverses itself, it appears necessary to employ something like the time neutral generalization of quantum mechanics [19, 20, 21, 22, 3] in which boundary conditions are imposed near both the big bang *and* the big crunch. These boundary conditions take the form of "initial" and "final" density operators[1] which, when CPT-reverses of one another, define what is meant here by a time symmetric universe.[2] In such a model the collection of quantum mechanical histories is time symmetric in the sense that each history in a decohering set (*i.e.* a set of histories in which relative probabilities may be consistently assigned) occurs with the same probability as its CPT-reverse [3, 23]. (As CP violation is small, there is for many purposes no difference between CPT- and T-symmetry with a T invariant Hamiltonian.) I do not describe these ideas in further detail because very little of the *formalism* of generalized quantum theory will be directly applied in this paper, but it is worth mentioning that in order for the resulting time symmetric quantum theory to have non-trivial predictions, the initial and final density operators must not represent pure states.[3] Interesting theories therefore have boundary conditions which are quantum

[1] I retain this terminology even though these operators may not be of trace class, for example in the familiar case where the final "boundary condition" is merely the identity operator on an infinite dimensional Hilbert space.

[2] In other words, the effective decoherence functional for matter in a time symmetric universe is a canonical decoherence functional $d(h,h') = \mathrm{tr}[\rho_\omega h^\dagger \rho_\alpha h']/(\mathrm{tr}\rho_\alpha \rho_\omega)$, with $\rho_\omega = (\mathcal{CPT})^{-1}\rho_\alpha(\mathcal{CPT})$ [3].

[3] As the first in an occasional series of comments directed to those familiar with the ideas of generalized quantum theory, this is because if the initial and final density operators are pure, at most two histories can simultaneously be assigned probabilities [3, 24, 25], *i.e.* the maximum number of histories in any weakly decohering set is two! Complete information about the history of the universe must be encoded in the boundary conditions. Details of the formalism of generalized quantum theory may be found in, *e.g.,* [26]. Generalized quantum mechanics with boundary conditions at two times is

statistical ensembles.

The interest in applying this class of quantum theories (namely, theories with CPT-related boundary conditions) in cosmology lies in the idea that the manifest arrow of time we observe is an emergent property of the universe, and not built directly into its structure by asymmetric dynamical laws or an asymmetric choice of boundary conditions. Dynamical laws are believed to be CPT-symmetric, so an asymmetric choice of boundary conditions is usually cited as the explanation for the existence of a definite arrow of time which flows in the same direction throughout the observable part of spacetime [12, 9, 13]. However, it is worth investigating whether this assumption is *required* of us by making the alternate, apparently natural ansatz that the boundary conditions on a closed universe are (in a relevant sense) equivalent at the beginning and end of time, instead of the more usual assumption that the initial condition is somehow special and the final condition one of "indifference," *i.e.* determined entirely by the past. Another point of view is that, as noted in [3], these alternative choices are in some sense opposite extremes. It is therefore of interest to determine whether they are distinguishable on experimental grounds, employing time symmetric boundary conditions as a laboratory for testing the sensitivity of physical predictions to the presence of a final boundary condition.

For the benefit of those eager to proceed to the definite physical predictions of sections 2 and 3, I now specify a model in which they might be expected to arise. (The cautiousness of this statement is explained in the sequel.) Sections 1.B, 3.B, and 4 elaborate on the physics expected in a universe with two-time, time symmetric boundary conditions; here I merely summarize what is required from those sections for a complete statement of the assumptions.

The model of the universe considered here consists in:

- A fixed closed, homogeneous and isotropic background spacetime, *viz.* a $k = +1$ Friedmann-Robertson-Walker (FRW) universe. The evolution of the scale factor is determined from Einstein's equations by the averaged matter content of the universe. (Inhomogeneities in the matter content can be treated as additional matter fields on this background.)

- Boundary conditions imposed on the matter content through a canonical decoherence functional $d_{\alpha\omega}$ [24] with CPT-related density operators ρ_α, ρ_ω that describe the state of matter at some small fiducial scale factor, near what would in the absence of quantum gravitational effects be the big bang and big crunch, but outside of the quantum gravity regime. The matter state described by one of these density operators reflects the presumed state of the early universe, namely matter fields in apparent thermal equilibrium at the temperature appropriate to the fiducial scale factor and the total amount of matter in the universe. Spatial fluctuations should be consistent with present day large scale structure, say being approximately scale invariant and leading to an amplitude of order 10^{-5} at decoupling in order to be consistent with recent COBE results [27]. Possible further conditions on ρ_α, ρ_ω are discussed at the end of this subsection.

The essence that a choice of boundary conditions with these apparently natural characterisics intends to capture is that of a universe in which the cosmological principle holds, which is smooth (and in apparent thermal equilibrium) whenever it is small, and which displays more or less familiar behaviour when larger. Most of the conclusions of this investigation really only rely on these general properties, but for the sake of definiteness a fairly specific model which has the right general physical characteristics is offered. However, as will be repeatedly emphasized in the sequel, in models with boundary conditions at two times, not only does the past have implications for the future, but the future has implications for the past. Therefore, in any attempt to model the *observed* universe with time symmetric boundary conditions, we need to make sure it is possible to integrate them into a self-consistent picture of the universe as we see it today. This means in particular that we must be prepared for the possibility that the early universe in a time symmetric universe may have properties different from those expected in a universe with an initial condition only. The model boundary conditions sketched above are not intended to be so restrictive as to rule out such differences, and hence must be taken with a grain of salt or two. The issue is then whether or not these properties are consistent with observation. Indeed, the prediction of an "excess" optical EGBR (to be discussed in section 3) in a universe with time symmetric boundary conditions is precisely of this character. (Of course, the most extreme possibility is that a

discussed more extensively in [3] and [24, 25].

universe burdened with these boundary conditions would look *nothing at all* like the universe in which we actually live.) Variations on this theme will recur frequently in the following sections.

With these boundary conditions [3], the time neutral generalized quantum mechanics of Gell-Mann and Hartle defines an effective quantum theory for matter in the universe which may be imagined to arise from some other, more fundamental, quantum cosmological theory of the boundary conditions. (Presumably, the fundamental quantum cosmological decoherence functional incorporates the quantum mechanics of the gravitational field as well, a complication that is not addressed in this paper.)

In this connection it is perhaps worth mentioning that it was once claimed [7] that the no-boundary proposal for the initial condition[28, [2] is an excellent review] implied just this sort of effective theory in that it appeared to require that the universe be smooth whenever it was small. Thus a fundamental theory of an initial condition *only* apparently could be decribed by an effective theory with *two-time* boundary conditions. However, this claim has since been recanted [17] due to a mathematical oversight. More generally, the no-boundary wave function does not appear to be a good candidate for a boundary condition imposed time symmetrically at both ends of a closed universe because it is a pure state [3], which as noted above yield quantum theories in which essentially all physical information is encoded in the boundary conditions alone. For contrast, see [11], in which it is asserted that the only sensible way to interpret the Wheeler-DeWitt equation necessitates a boundary condition requiring the universe to be smooth whenever it is small.

In order to allow definite predictions to be made, the final key assumption of the model is that, for a suitable class of physically interesting coarse grainings (*e.g.* coarse grainings defining the domain of classical experience, or local quantum mechanics experiments), the probabilities for such coarse grained physical histories unfold near either boundary condition (relative to the total lifetime of the universe) in a fashion insensitive to the presence of the boundary condition at the other end, *i.e.* as if the other boundary condition were merely the identity. As discussed in section 1.B, simple stochastic models [19, 3, 29, 30, 31] suggest that this holds for processes for which the "relaxation time" of the process to equilibrium is short compared to the total time between the imposition of the boundary conditions (see section 1.B), which expectation is rigorously supported in the case of Markov processes [32]. Therefore, for the sake of brevity this predictive ansatz shall often be referred to as the "Relaxation Time Hypothesis" (RTH). A more careful statement of the RTH would identify the classes of coarse grained histories (presumably at least those decribing short relaxation time processes at times sufficiently close to, for instance, the big bang) for which conditional probabilities (when defined) are, in a universe with boundary conditions ρ_α, ρ_ω, supposed to be close to those of a universe with $\rho_\omega = 1$.[4] It would also define "close" and "short relaxation time process" more precisely. (Thus, a rigorous statement of what is meant by the RTH requires a definite mathematical model. Because the concerns of this investigation encompass a variety of complicated physical processes, with the entire universe considered as a single physical system, I do not attempt that here. In specific cases the intuitive content of the ansatz ought to be clear enough.) In order to exploit the RTH to its fullest, I shall, when convenient, assume also that the universe is close to the critical density, so that its lifetime is very long. This plausibly realistic assumption maximizes the possibility that a model of the kind given above accurately describes our universe.

With these assumptions, this model universe might be expected to closely resemble the universe as it is observed today *if* most familiar and important physical processes are examples of such "short relaxation time processes." In particular, under the assumption that they are, predictions we expect of a single initial condition ρ_α only (*i.e.* $\rho_\omega = 1$) can (by the RTH) be assumed to hold near the initial condition in the model with CPT-related initial and final conditions. Such predictions should include those regarding inflation, relative particle abundances, and the formation of large (and small) scale structure. Because of the CPT-related boundary condition at the big crunch, a qualitatively similar state of affairs is then expected in the recollapsing era, but CPT reversed. As the thermodynamic arrow is caused fundamentally by gravitational collapse driving initially smooth matter away from equilibrium [15, 9, for example], the arrow of entropy increase near the big crunch will run in the opposite direction to that near the big bang.[5] Observers on planets in the recollapsing phase will find their situation

[4] Some subtleties regarding equivalences between boundary conditions at one and two times are being concealed here, for which see [25].

[5] Some discussion of the state of the universe when it is large, which somehow must interpolate between these opposed thermodynamic arrows, is provided in sections 1.B, 3.B, and 4.

indistinguishable from our own, with all time arrows aligned in the direction of increasing volume of the universe. It is this interesting (if unconventional) state of affairs which leads to the conclusion that observations of the EGBR can reveal the presence of a final boundary condition that is CPT-related to the initial, even if the lifetime of the universe is very great. How this comes about is the topic of section 3.

Before proceeding, some points made in the preceeding paragraph require qualification. (Readers whose only interest is the extragalactic background radiation should procede directly to section 2. This discussion, and that of the next subsection, are positioned here for the sake of unity and perspective.) First, the “relaxation times” for many important physical processes in a recollapsing universe *do not* appear to be short compared to the lifetime of the universe, even if that lifetime is arbitrarily long. The result described in section 2, that light from the present epoch can propagate unabsorbed into the recollapsing phase, is an excellent example of this [1, 3]. Some physical difficulties with the consistency of time symmetry to which this gives rise will become apparent in section 3.B. Further examples of such physical difficulties relating to issues such as gravitational collapse, the consequent emergence of a familiar thermodynamic arrow, and baryon decay in a universe with time symmetric boundary conditions are discussed briefly in section 4. The self-consistency of such models is thus in doubt, with these kinds of complications constituting arguments against the possibility that our universe possesses time symmetric boundary conditions. That is, it appears that time symmetry is *not* consistent with the central predictive ansatz that physics near either boundary condition is practically insensitive to the presence of the other, and it appears likely that a universe with time symmetric, low (matter) entropy boundary conditions would look *nothing like* the universe in which we actually live. Nevertheless, the strategy of sections 2 and 3 is to assume that the time symmetric picture is consistent with the gross characteristics of the observed universe and see what it predicts. Because of the prediction of a diffuse optical extragalactic background radiation that is testably different from that in a universe which is not time symmetric, we are provided with a two pronged attack on the hypothesis of time symmetric boundary conditions as a realistic description of our universe: the lack of a self-consistent picture of the observed universe, and observations of the EGBR.

Second, for completeness it should be mentioned that in the context of the time neutral generalized quantum mechanics assumed here, there are further restrictions on the viability of time symmetric models as a realistic description of our universe which arise from the requirements of decoherence and the emergence of approximately classical behaviour.[6] These topics are discussed by Gell-Mann and Hartle [3].

Third, it is important to note that the conclusions of section 3 regarding the EGBR depend essentially on the assumed *global* homogeneity and isotropy, *i.e.* the “cosmological principle.” Thus, while inflation (apparently a generic consequence of quantum field theory in a small universe) can be taken to be a prediction of the assumed boundary conditions if they are imposed when the universe is sufficiently small, the popular point of view (somewhat suspect anyway) that inflation provides an *explanation* of homogeneity and isotropy inside the horizon is not a prediction of the effective theory of the universe considered here; it is an assumption. However, the other good things inflation does for us would still qualify as predictions.

One further point requires mention. In the conventional picture of inflation, the matter in the universe is in a pure state (say, some vacuum state) when small. After inflation and reheating the matter fields appear to be, according to local coarse grainings, in thermal equilibrium, the states of different fields being highly entangled. Furthermore, the correlations required to infer that the complete state is actually pure have been inflated away. Nevertheless, the quantum state is of course still pure [33]. As noted previously, pure states are not viable candidates for the initial and final conditions. Therefore, in order to fit the conventional picture of inflation into an effective theory of the kind considered in this paper, the ρ_α and ρ_ω defined above must be a local description in the sense that they not contain the information required to know that the state from which they were inferred was actually pure, *i.e.* they must coarse-grain this information away. (The alternative is to employ an inflationary scenario in

[6] It is not obvious that boundary conditions of the character noted above satisfy these restrictions, but if sufficient conditions obtain for the RTH to hold then it is at least plausible that they do. This is because such requirements might be expected to be more severe the more strongly correlated are the detailed states of the expanding and recollapsing eras. This should become clearer in section 1.B.

which the universe is not required to be in a pure state.) The unpleasantness of this restriction could be taken as an argument against the use of CPT-related boundary conditions in a fundamental quantum cosmological theory.

Finally, for the cognoscenti of generalized quantum mechanics [26, for example], there is a related observation that is even more interesting. Field theoretic Hamiltonians are CPT-invariant, so that if the CPT-related ρ_α and ρ_ω depend only on the Hamiltonian (as for instance an exactly thermal density operator does), ρ_α and ρ_ω are actually *equal*. (The same observation holds for merely T-related boundary conditions if the Hamiltonian is T invariant. However, CPT seems the more relevant symmetry if the Hamiltonian and boundary conditions of the considered effective theory of the universe arise from some more fundamental theory.) This is a potential difficulty for the sample model given above. A simple extension of a result of Gell-Mann and Hartle [3, section 22.6.2] to the case where the background spacetime is an expanding universe shows that the only dynamics allowed with identical initial and final boundary conditions is trivial: for alternatives allowed in sets of histories in which probabilities may be assigned at all, the time dependence of probabilities for alternative outcomes is essentially *independent of the Hamiltonian*, and is due only to the expansion of the universe.[7] In the present case this may be interpreted as a prediction that a universe which is required to be in thermal equilibrium whenever it is small *must remain so when large,* at least in the context of the theoretical structure of Gell-Mann and Hartle. (Classically the expectation is the same, so this result can hardly be written off as an artifact of the formalism.) Now, the evidence suggests that matter in the the early universe *was* in local thermal equilibrium. However, the inhomogeneities in the matter required to generate large scale structure must also be described by the boundary conditions, and, even in the usual case where there is only an initial condition, it is after all gravitational condensation which drives the appearance of a thermodynamic arrow.[8] In the present case (the model with the two-time boundary conditions characterized above), the meaning of these observations is that one way to break the CPT invariance of the boundary conditions is for the specification of the deviations from perfect homogeneity and isotropy to be CPT non-invariant, in order that the theory admit interesting dynamics. As a specific example, I briefly consider the common circumstance where cosmological matter is given a hydrodynamic description. Scalar-type adiabatic pertubations may be completely specified by, *e.g.,* the values of the energy density perturbation and its (conformal-) time derivative over a surface of constant conformal time [34]. (Scalar-type pertubations are the ones of interest, as they are the ones which may exhibit instability to collapse.) As it is intended here that gravity is treated classically, such a specification might come in the form of a probability distribution for approximately scale invariant metric and energy density fluctuations averaged over macroscopic scales. If this probability distribution reflects the underlying FRW homogeneity and isotropy (and is thus in particular P-invariant), in order to break T-invariance the distribution must distinguish between opposing signs of the (conformal-) time derivatives of the energy density perturbations. An alternative way to break the equality of CPT-related boundary conditions is for the locally observed matter-antimatter asymmetry to extend across the entire surface of constant universal time. (The recollapsing era will then be antimatter dominated in a CPT symmetric universe, consequently requiring that there be some mechanism to permit baryon decay.) This possibility may appear more attractive, but it is not without significant complications. These are addressed briefly at the end of section 3.B.

1.B Physics with Time Symmetric Boundary Conditions

As noted above, the time neutral generalized quantum mechanics of Gell-Mann and Hartle [3] with CPT-related initial and final density operators yields a CPT symmetric ensemble of quantum mechanical histories, in the sense that each history in the collection is accompanied with equal probability by its CPT-reverse. The *collection* of histories (in each decohering set) is therefore statistically time symmetric

[7] To be more precise, consider the projections which appear in sets of histories that decohere for some $\rho_\alpha = \rho_\omega$. For time independent Hamiltonians, time dependence of probabilities for such projections arises only if the projections are time-dependent in the Schrödinger picture. Due to the expansion, this will be the case for many projections onto (otherwise time-independent) quantities of physical interest in an expanding universe.

[8] More precisely, smoothly distributed matter in thermal equilibrium is *not* an equilibrium state when the gravitational field is included. Equilibrium states in the presence of gravitation have clumpy matter in them.

(STS). Now, a set of histories can be statistically time symmetric without any individual history possessing qualitatively similar (if time-reversed) characteristics near both ends. Completely time asymmetric histories can constitute a statistically time symmetric set if each history in the collection is accompanied by its time reverse [3, 23]. With two-time boundary conditions, however, more is required. That is, there is a distinction between a CPT invariant *set* of histories, in which each history in a decohering set is accompanied, with equal probability, by its CPT reverse, and the considerably more restrictive notion of a statistically time symmetric universe studied here. In virtue of the boundary conditions at both the beginning and the end of time, probable histories (in a set which decoheres with these boundary conditions) will in general have both initial and final states which to some extent resemble the boundary conditions ρ_α, ρ_ω [25].

Perhaps the clearest way to understand this is to consider the construction of a classical statistical ensemble with boundary conditions at two times. The probability for each history in the ensemble may be found in the following way [19, 3]. The boundary conditions are given in the form of phase space probability densities for the initial and final states of the system. Pick some initial state. Evolve it forward to the final time. Weight this history by the product of the probabilities that it meets the initial and final conditions, and divide by a normalizing constant so that all the probabilities sum to one. Thus, roughly speaking, in order for a history to be probable in this two-time ensemble both its initial and final state must be probable according to the initial and final probability densities, respectively. (For a deterministic classical system, two-time statistical boundary conditions are equivalent to a boundary condition at one time constructed in the obvious way. In quantum mechanics this is no longer true due to the non-commutability of operators at different times. Thus, while the described algorithm is merely a useful heuristic for understanding the implications of two-time boundary conditions *classically*, it is more essential quantum-mechanically.) What is not so clear is that the resulting probable histories look anything like the probable histories in the ensemble with just, say, the initial condition. In general they will not. Classically, this is merely the statement that the probability measure on a space of classical deterministic solutions defined by two-time boundary conditions will in general be quite different than the measure defined by the initial probability density only.

For classical systems with stochastic dynamics or for quantum statistical systems, the simple models studied by Cocke [19], Schulman [29, 30, 31, 32], and others yield some insight into what is required for evolution near either boundary condition to be influenced only by that boundary condition. Here I merely summarize the intuitively transparent results of this work in the context of time symmetric boundary conditions. In particular, the emphasis will be on boundary conditions which represent "low entropy" initial and final states.

In the absence of a final condition, an initially low entropy state generally implies that evolution away from the initial state displays a "thermodynamic arrow" of entropy increase (relative to the coarse graining defining the relevant notion of entropy; see [9] for a pertinent overview.) In an ensemble with two-time, time symmetric, low entropy boundary conditions, under what conditions will a familiar "thermodynamic arrow" appear near either boundary condition? A pertinent observation is that, roughly speaking, in equilibrium all arrows of time disappear. Therefore, if the total time between the imposition of the boundary conditions is much longer than the "relaxation time" of the system to equilibrium (defined as the characteristic time a similar system with an initial condition only takes to relax), it might be expected that entropy will increase in the familiar fashion away from either boundary condition. That is, following the coarse-grained evolution of the system forward from the initial condition, entropy increases at the expected rate until the system achieves equilibrium. The system languishes in equilibrium for a time, and then entropy begins to decrease again until the entropy reaches the low value demanded by the final condition. Thus, this is a system in which the "thermodynamic arrow of time" reverses itself, which reversal is enforced by the time symmetric, low entropy boundary conditions. There is no cause to worry about the coexistence of opposed thermodynamic arrows. Histories for which entropy increases away from either boundary condition are readily compatible with both boundary conditions, and the probable evolutions are those in which, *near either boundary condition*, there is a familiar thermodynamic arrow of entropy increase away from the nearest boundary condition. There, the other boundary condition is effectively invisible. Essentially this is because in equilibrium all states compatible with constraints are equally probable; the system "forgets" its boundary conditions.

On the other hand, if there is not time enough for equilibrium to be reached there must be some reconciliation between the differing arrows of increasing entropy [19, 12, 15, 35, 3, 32]. As only histories which satisfy the required boundary conditions are allowed, it can be anticipated that the statistics of physical processes that would ordinarily (in the absence of the final boundary condition) lead to equilibration would be affected because histories which were probable with an initial condition only are no longer compatible with the final condition. The rate of entropy increase is slowed, and in fact the entropy may never achieve its maximum value. In other words, the approach to equilibrium is suppressed by the necessity of complying with the low entropy boundary condition at the other end. More probable in this two-time ensemble is that the state *will continue to resemble the low entropy boundary conditions.* The entire evolution is sensitive to the presence of *both* boundary conditions.

In fact, as noted already, simple models of statistical systems with a boundary condition of low entropy at two times bear out these intuitively transparent expectations [19, 29, 30, 31]. Moreover, in the case of Markov processes Schulman has demonstrated the described behaviour *analytically* [32]. This confluence of intuitive clarity, and, for simple systems, analytic and (computerized) experimental evidence will be taken as suggestive that the significantly more complicated physical system considered in this work (matter fields in a dynamic universe) behaves in a qualitatively similar fashion when burdened with time symmetric boundary conditions.[9]

The lesson of this section is that the place to look for signs of statistical time symmetry in our universe is in physical processes with long "relaxation times," or more generally in any process which might couple the expanding and recollapsing eras [3]. Such processes might be constrained by the presence of a final boundary condition. Obvious candidates include decays of long-lived metastable states [5, 6, 30, 32, 3], gravitational collapse [15, 35, 36, see also [30]] and radiations [1, 3] with great penetrating power such as neutrinos, gravitational waves, and possibly electromagnetic radiation. Thus, there are a variety of tests a cosmological model with both an initial and a final condition must pass in order to provide a plausible description of our universe.

The next two sections discuss the extragalactic background radiation as an example of a physical prediction that is expected to be sensitive to the presence of a final boundary condition (time symmetrically related to the initial.) I focus on electromagnetic radiation because it is the most within our present observational and theoretical grasp, but the essence of the discussion is relevant to any similar wave phenomenon. Finally, in section 4 I offer a few comments on some other issues that need to be addressed in any attempt to describe our universe by a model such as the one sketched in section 1.A.

2 The Opacity of the Future Light Cone

The aim of this section is to extend arguments of Davies and Twamley [1] showing that a photon propagating in intergalactic space is likely to survive until the epoch of maximum expansion (assuming the universe to be closed), no matter how long the total lifetime of the universe. That is, the future light cone is essentially transparent over a wide range of frequencies for extinction processes relevant in the intergalactic medium (IGM), with an optical depth of at most $\tau \sim .01$ at optical frequencies. The physics in this result is that, in cases of physical interest, the dilution of scatterers due to the expansion of the universe wins out over the extremely long path length the photon must traverse. As a consequence, the integrated background of light from galaxies in the expanding phase will still be present in the recollapsing phase. (As explained in section 3, it is this fact which implies that there is an "excess" EGBR in a time symmetric universe that is not associated with galaxies to our past.) To show this, I compute, for a fairly general class of absorption coefficients, the optical depth between the present epoch and the moment of maximum expansion. For realistic intergalactic extinction processes this optical depth turns out to be small. Indeed, the opacity of the future light cone turns out to be

[9] Of course, the physics must at the completely fine-grained level be consistent with whatever dynamics the system obeys, including such constraints as conservation laws. As a moment's reflection on classical Hamiltonian systems with two-time phase space boundary conditions reveals, this may be a severe constraint! A purely stochastic dynamics (no dynamical conservation laws) allows systems great freedom to respect the RTH, and conclusions drawn from the behaviour of such systems may therefore be misleading. The restrictions on sensible boundary conditions in time neutral generalized quantum mechanics noted in the last paragraphs of section 1.A (which arise essentially as a result of the requirements of decoherence) are examples of phenomena with no counterpart in stochastic systems. See also the discussion of gravitational collapse in section 4.A.

dominated by "collisions" of intergalactic photons with other galaxies, if they are regarded as completely opaque hard spheres. Even in the limit that the lifetime of the universe T becomes infinite ($\Omega \to 1$ from above) all of the relevant processes yield finite optical depths. As this is essentially the limit of a flat universe, it is no surprise that extremely simple expressions result.

The results of this section are modest extensions of the work of Davies and Twamley [1]. For the intergalactic extinction mechanisms and at the frequencies they consider, the formulae for the opacity derived here give numbers in agreement with their results (using the same data for the IGM, of course.) The present work is of slightly broader applicability in that the opacity is evaluated for a fairly general class of frequency dependent extinction coefficients (not just for a few specific processes), and its behaviour as the lifetime of the universe becomes arbitrarily long is determined. It turns out that quite generally, the asymptotic limit is in fact of the order of magnitude of the *upper* limit to the opacity in a closed universe. These results are less general than that of [1] in that I do not include the effects of a cosmological constant (which makes the perturbative analysis below significantly more awkward.) However, a small cosmological constant does not effect the qualitative nature of the conclusions of this section.

2.A The Future Light Cone Can Be Transparent

Optical depth τ is defined by

$$d\tau = \Sigma\, dl, \tag{2.1}$$

where Σ, the linear extinction coefficient, is the fractional loss of flux per unit (proper) length l, and is given microscopically by

$$\Sigma = \sigma n \tag{2.2}$$

for incoherent scattering from targets with cross section σ and proper number density n (this neglects stimulated emission and scattering into the line of sight.) Given τ, the flux density along the line of sight thus obeys

$$i(l) = i_0 e^{-\tau(l)}. \tag{2.3}$$

Put another way, the probability a photon will propagate a distance l without being absorbed is $e^{-\tau(l)}$. For further details, see for example [37].

In order to compute τ we need $\Sigma(l)$. In the approximation (appropriate to the calculation of optical depths between the present and the moment of maximum expansion) that the universe is exactly described by closed, dust-filled Friedmann-Robertson-Walker, it turns out to be helpful to trade in the dependence on proper length for time. The metric is

$$ds^2 = a^2\,[-d\eta^2 + d\Omega_3^2], \tag{2.4}$$

where

$$d\Omega_3^2 = d\chi^2 + \sin^2\chi\, d\Omega_2^2 \tag{2.5}$$

is the metric on the unit 3-sphere, and

$$dt = a\, d\eta \tag{2.6}$$

relates the cosmological time (proper time in the cosmological rest frame) to the conformal time η. For dust the time dependence of the scale factor a can be expressed parametrically as

$$a(\eta) = M\,(1 - \cos\eta), \tag{2.7}$$

so that

$$t(\eta) = M\,(\eta - \sin\eta). \tag{2.8}$$

The lifetime of the universe is then $T = 2\pi M$. Here $M = \frac{4\pi}{3}\rho a^3$ is a constant as the universe expands, ρ being the mass density of the dust. M is related to more familiar cosmological parameters by

$$M = \frac{1}{H_0}\frac{q_0}{(2q_0 - 1)^{\frac{3}{2}}}. \tag{2.9}$$

Employing the symmetry of the model to take a photon's path as radial, $ds^2 = 0$ gives $dl = dt = a\,d\eta$, from which

$$d\tau = \Sigma a\,d\eta. \tag{2.10}$$

The high symmetry of Friedmann-Roberston-Walker also means that nearly all the relevant physical quantities simply scale as a power of a. Thus, as will be seen explicitly in the next subsection, it is necessary to consider only extinction coefficients of the form

$$\Sigma = \Sigma_0 \left(\frac{a_0}{a}\right)^{p+1}, \tag{2.11}$$

where a_0 is some fiducial scale factor (conventionally the present one) and p is a number.

The goal is to compute the optical depth between now and the moment of maximum expansion. "Now" will be taken to be the time t_0 from the big bang to the present. For absorption coefficients of the form (2.11), the optical depth of the future light cone is

$$\begin{aligned} \tau &= \int_{\tau(t_0)}^{\tau(T/2)} d\tau \\ &= \int_{\eta_0}^{\pi} \Sigma\, a\, d\eta \\ &= \Sigma_0\, t_0\, g_p(\eta_0) \end{aligned} \tag{2.12}$$

using (2.7) and (2.10). Here η_0 is the conformal time of the present epoch, and $g_p(\eta_0)$ is the dimensionless function

$$\begin{aligned} g_p(\eta_0) &\equiv \left(\frac{M}{t_0}\right)\left(\frac{a_0}{M}\right)^{p+1} \int_{\eta_0}^{\pi} \frac{d\eta}{(1-\cos\eta)^p} \\ &= \frac{(1-\cos\eta_0)^{p+1}}{\eta_0 - \sin\eta_0} \int_{\eta_0}^{\pi} \frac{d\eta}{(1-\cos\eta)^p}. \end{aligned} \tag{2.13}$$

For integral and half-integral p explicit evaluation of $g_p(\eta_0)$ is possible, but not terribly illuminating. In the limit that the total lifetime of the universe T is very long compared to t_0, however, simple expressions for any p result. (This is no surprise as the results must approach those of a flat universe.) One straightforward procedure involves inverting (2.8) to get a power series in $\left(\frac{t_0}{M}\right)^{\frac{1}{3}}$ for η_0, and using this to evaluate the asymptotic behaviour of $g_p(\eta_0)$ as M becomes large relative to t_0, which is held fixed. ($T = 2\pi\, M \gg t_0$ corresponds to $\eta_0 \ll 1$.) It is then tedious but straightforward to show that

$$g_p \sim \begin{cases} \frac{3}{2p-1}\left[1 + \frac{p+1}{10(2p-3)}\left(\frac{6t_0}{M}\right)^{\frac{2}{3}}\right] & p > \frac{1}{2}\ ;\ p \neq \frac{3}{2} \\ \frac{3}{2}\left[1 - \frac{1}{12}\left(\frac{6t_0}{M}\right)^{\frac{2}{3}} \ln\left(\frac{6t_0}{M}\right)\right] & p = \frac{3}{2} \\ \ln\left(\frac{M}{t_0}\right)\left[1 - \frac{3}{40}\left(\frac{6t_0}{M}\right)^{\frac{2}{3}}\right] & p = \frac{1}{2} \\ 3\pi\frac{\Gamma(1-2p)}{\Gamma^2(1-p)}\left(\frac{M}{6t_0}\right)^{\frac{1-2p}{3}} - \frac{3}{1-2p} & -\frac{1}{2} < p < \frac{1}{2} \\ 12\left(\frac{M}{6t_0}\right)^{\frac{2}{3}} - \frac{9}{5} & p = -\frac{1}{2} \\ 3\pi\frac{\Gamma(1-2p)}{\Gamma^2(1-p)}\left(\frac{M}{6t_0}\right)^{\frac{1-2p}{3}}\left[1 - \frac{p+1}{20}\left(\frac{6t_0}{M}\right)^{\frac{2}{3}}\right] & p < -\frac{1}{2} \end{cases} \tag{2.14}$$

In each case only the leading order correction in $\frac{t_0}{M}$ has been retained. The most important thing to notice is that for $p > \frac{1}{2}$, g_p is perfectly finite even as the lifetime of the universe becomes arbitrarily big, and as $\frac{t_0}{M}$ becomes very small the opacity converges to the value it would have in a flat universe. It is clear that for $p > \frac{3}{2}$ the $\Omega_0 = 1$ result is a local lower limit on the opacity of the future light cone, as may be verified directly also from the available exact results. However, for reasonable p the corrections to the flat universe result are only a factor of order one. (In fact, examination of the exact results reveals that the *maximum* of g_p as one varies $\frac{t_0}{M}$ is at most 20% larger than the flat universe result for $p \sim$ few.

This is a good thing, because unless Ω is fairly close to one, $\frac{t_0}{M}$ is not a particularly small parameter! In terms of familiar cosmological parameters,

$$\frac{t_0}{M} = \left[\cos^{-1}({q_0}^{-1} - 1) - {q_0}^{-1}(2q_0 - 1)^{\frac{1}{2}}\right].) \tag{2.15}$$

Physically, what's at work is the competition between the slower expansion rates of universes with larger Ω_0's, which tends to increase the opacity because the scattering medium isn't diluted as rapidly, and the decrease in the opacity due to the shortened time between the present epoch and the moment of maximum expansion.[10]

To summarize, all of the processes relevant to extinction in the intergalactic medium have extinction coefficients that can be bounded above by a coefficient of the form (2.11) with $p > \frac{1}{2}$. Using the limiting relationship $t_0 = \frac{2}{3H_0}$, we have from (2.12) and (2.14) the simple result that for these processes, the upper limit to the opacity between the present epoch and the moment of maximum expansion, no matter how long the total lifetime of the universe, is of order

$$\tau = \frac{2}{2p-1}\frac{\Sigma_0\, c}{H_0}. \tag{2.16}$$

(I have returned to conventional units in this formula.)

2.B The Opacity of the Future Light Cone

In this section I apply the asymptotic formula (2.16) for the upper limit to the optical depth of the FLC in a long-lived universe to show that if our universe is closed, photons escaping from the galaxy are (depending on their frequency) likely to survive into the recollapsing era. That is, the finite optical depths computed in the previous section are actually small for processes of interest in the intergalactic medium (IGM). For simplicity, I focus on photons softer than the ultraviolet at the present epoch; the cosmological redshift makes it necessary to consider absorption down to very low frequencies.

It is important to note that in employing standard techniques for computing opacities the effects of the assumed statistical time symmetry of the universe are being neglected. As discussed in section 1.B and in section 4, when the universe is very large the thermodynamic and gravitational behaviour of matter will begin to deviate from that expected were the universe not time symmetric. Due to the manifold uncertainties involved here it is difficult to approach the effects of time symmetric boundary conditions on the opacity of the future light cone with clarity.[11] I shall assume they are not such as to increase it. This is reasonable as the dominant contribution to the opacity comes when the universe is smallest, where in spite of the noted complications the RTH is assumed to hold.

What are the processes relevant to extinction of photons in the intergalactic medium? Because the IGM appears to consist in hot, diffuse electrons, and perhaps a little dust [38], extinction processes to

[10] It will be noticed by combining (2.9) and (2.15) that taking the limit $\Omega_0 \to 1$ holding t_0 fixed requires H_0 to vary as well, converging to the flat universe relation $H_0 = \frac{2}{3t_0}$. It is possible to repeat the entire analysis holding the observable quantity H_0 fixed instead of t_0 (for this purpose the more standard redshift representation is more useful than that in terms of conformal time used above), but unsurprisingly the conclusions are the same: the opacity is always finite for $p > \frac{1}{2}$; as Ω_0 approaches one, the opacity approaches the flat universe result; and the *maximum* opacity for reasonable p is only a factor $\lesssim 1.2$ times the flat universe result. The resultant opacities are of course related in these limits via $t_0 = \frac{2}{3H_0}$. Similarly, it is possible to perform a related analysis of more complicated extinction coefficients than (2.11), for example incorporating the exponential behaviour encountered in free-free absorption (see (2.23)) or in modeling evolving populations of scatterers with, for instance, a Schecter function type profile. However, these embellishments are not required in the sequel, and the techniques are tedious and fairly ordinary, so space will not be taken to describe them here.

[11] For example, how is scattering of light by a "thermodynamically reversed" medium to be treated, as when light from the expanding era reaches the intergalactic medium in the recollapsing phase? The standard account assumes incoherent scattering. Thus a laser beam shone on a plasma is diffused. Time-reversing this description yields *extremely* coherent scattering from the plasma which reduces its entropy. Thus scattering or absorption of light correlated with sources (such as galaxies) in the expanding phase by material in the recollapsing phase appears to require entropy reducing (according to the observers of the recollapsing era) correlations in the matter there, in contradiction with the presumed local thermodynamic arrow (and with the RTH), in order to yield what there appears as emission. This is just the sort of detailed connection between the expanding and recollapsing eras which would lead one to expect physical predictions in a time symmetric model, even very near one of the boundary conditions, to be very different than those in a model with an initial condition only (section 1.B). This complication is closely related to the difficulty, mentioned in section 4.B, in deriving the retardation of radiation in a universe which is time symmetric and in which the future light cone is transparent.

include are Thomson scattering, inverse bremsstrahlung (free-free absorption), and absorption by dust. In addition, absorption by material in galaxies (treated as completely black in order to gauge an upper limit) is important. These processes will treated in turn. (A useful general reference on all these matters is [37].) The conclusion will be that while absorption by galaxies and Thomson scattering are most significant above the radio, none of these processes pose a serious threat to a photon that escapes from our galaxy. This confirms the results of Davies and Twamley [1], who however did not consider the possibly significant interactions with galaxies. Consequently I will be brief. Some results of Davies and Twamley regarding absorption mechanisms which may be important when the universe is very large and baryons have had time to decay are quoted at the end of this section. These do not appear to be significant either.

(For high energy photons Compton scattering, pair production, photoelectric absorption by the apparently very small amounts of neutral intergalactic hydrogen, and interactions with CMBR photons will be important, but as none are significant below the ultraviolet I do not discuss them here. All can be treated by the same methods as the lower energy processes.)

To begin, following Davies and Twamley [1], I quote Barcons *et al.* [38] on current beliefs regarding the state of the IGM in the form

$$\begin{aligned} n_{\mathrm{H_{II}}} &= \delta\, n_0 \left(\frac{a_0}{a}\right)^3 \\ T_{\mathrm{H_{II}}} &= \epsilon\, T_0 \left(\frac{a_0}{a}\right)^2 \end{aligned} \tag{2.17}$$

where

$$\begin{aligned} n_0 &= 1.12\, h^2\, 10^{-7}\ \mathrm{cm}^{-3}, \quad \delta \in (1, 10) \\ T_0 &= 10^4\ \mathrm{K}, \quad \epsilon \in (1, 10^3) \end{aligned} \tag{2.18}$$

with the values $\delta = \epsilon = 1$ somewhat preferred by the authors. In addition, the present upper limit on a smoothly distributed component of neutral hydrogen is about $n_{\mathrm{H_I}} < 10^{-12}\ \mathrm{cm}^{-3}$. Thus, the intergalactic medium consists in hot (but non-relativistic) electrons, protons, and essentially no neutral hydrogen. The lack of distortions in the microwave background indicates its relative uniformity, at least to our past. From now on, n and T simply will be used to refer to the number density and temperature of intergalactic electrons.

Finally, very little is known about a possible diffuse component of intergalactic dust [38, 39], except that there is probably very little of it. Most dust seems to be clumped around galaxies. Therefore I will ignore possible extinction due to it, subsuming it into the "black galaxy" opacity. Davies and Twamley [1] make some estimates for one model for the dust, finding its contribution to the opacity insignificant. At any rate, models for the absorption coefficient due to dust [40, 41] all give a cross section σ that falls with increasing wavelength, $\sigma \sim 1/\lambda^q$ with $1 \leq q \leq 4$, so that $\Sigma = \sigma\, n \propto \left(\frac{a_0}{a}\right)^{q+3}$ (neglecting of course a clumping factor expressing the fact that clumping decreases the opacity.) Thus $p_{\mathrm{dust}} = q + 2 > \frac{1}{2}$, the dust opacity is bound to be finite, and with a small present density of diffuse dust it is not surprising to find its contribution to be small.

Before considering the optical depth due to interactions with intergalactic electrons, I will show that it is reasonable to approximate that most photons escaping our galaxy will travel freely through intergalactic space. That is, few photons will end up running into another galaxy.

Collisions with Galaxies

Drastically overestimating the opacity due to galaxies by pretending that any photon which enters a galaxy or its halo will be absorbed by it (the "black galaxy" approximation), and taking the number of galaxies to be constant,

$$\begin{aligned} \Sigma_{\mathrm{gal}} &= \sigma\, n \\ &= \sigma\, n_0 \left(\frac{a_0}{a}\right)^3, \end{aligned} \tag{2.19}$$

where σ is the cross-sectional area of a typical galaxy and n_0 is their present number density. Thus from (2.16), the upper limit on the opacity due to collisions with galaxies is

$$\tau = \frac{2}{3}\frac{\sigma\, n_0\, c}{H_0}. \tag{2.20}$$

As noted above, this is finite (even as the lifetime of the universe becomes very large) because the dilution of targets due to the expansion of the universe is more important than the length of the path the photon must traverse.

Notice that assuming target galaxies to be perfectly homogeneously distributed only overestimates their "black galaxy" opacity. Volume increases faster than cross-sectional area, so clustering reduces the target area for a given density of material. As galaxy clustering is not insignificant today and will only increase up to the epoch of maximum expansion even in a time symmetric universe, the degree of overestimation is likely to be significant.

Taking $n_0 \sim .02\, h^3$ Mpc^{-3}, $\sigma = \pi\, r_{\rm gal}^2$ (where $r_{\rm gal} \sim 10^4\, h^{-1}$ pc), and $H_0 \sim \frac{1}{3}\cdot 10^{-17}\, h$ s^{-1} (here $.4 < h < 1$ captures as usual the uncertainty in the Hubble constant) gives the upper limit

$$\tau \sim .01. \tag{2.21}$$

This can be interpreted as saying that at most about one percent of the lines of sight from our galaxy terminate on another galaxy before reaching the recollapsing era. By time symmetry, neither do most lines of sight connecting the present epoch to its time-reverse.

Thomson Scattering

Use of the Thomson scattering cross section $\sigma_{\rm T} = \frac{8\pi}{3} r_0^2 = 6.65 \cdot 10^{-25}$ cm^{-2} is acceptable for scattering from non-relativistic electrons for any photon softer than a hard X-ray ($\hbar\omega \ll mc^2$). Thus, for the frequencies I will consider, $\Sigma_{\rm T} = \sigma_{\rm T} n$ will suffice, giving

$$\begin{aligned} \tau_{\rm T} &= \frac{2}{3}\frac{\delta\sigma_{\rm T} n_0 c}{H_0} \\ &= 4.7(\delta h)10^{-4}. \end{aligned} \tag{2.22}$$

Recalling that δ is at worst one order of magnitude, it is clear that Thomson scattering is not signficant for intergalactic photons [1]. It is perhaps worth mentioning that quantum and relativistic effects only tend to decrease the cross section at higher energies. More significant for the purposes of this investigation is the observation that, at the considered range of frequencies, Thomson scattering does not change a photon's frequency, merely its direction. Thus Thomson scattering of a homogeneous and isotropic bath of radiation by a homogeneous and isotropic soup of electrons has *no effect* as regards the predictions of section 3.[12]

Inverse Bremsstrahlung

Even less significant than Thomson scattering for frequencies of interest is free-free absorption by the IGM [1]. From, *e.g.* [37], the linear absorption coefficient for scattering from a thermal bath of ionized hydrogen is

$$\begin{aligned} \Sigma_{\rm ff} &= \frac{2e^6}{3m\hbar c}\left(\frac{2}{3\pi k m}\right)^{\frac{1}{2}} n^2 T^{-\frac{1}{2}} \nu^{-3} \overline{g}(b)(1-e^{-b}) \\ &= 3.7\cdot 10^8 n^2 T^{-\frac{1}{2}} \nu^{-3} \overline{g}(b)(1-e^{-b})\,\mathrm{cm}^{-1}. \end{aligned} \tag{2.23}$$

in cgs units. Here $b \equiv \frac{h\nu}{kT}$, the factor e^{-b} contains the effect of stimulated emission, and $\overline{g}(b)$ is a "Gaunt factor" expressing quantum deviations from classical results. It is a monotonically decreasing function

[12] Were it significant, it would however be a means of hiding the *information* contained in the background.

of b which is of order one in the optical (*cf.* [37] for a general discussion and some references.) As

$$\begin{aligned} b &= \frac{h\nu}{kT} \\ &= \frac{h\nu_0}{kT_0}\left(\frac{a}{a_0}\right) \end{aligned}$$

increases as the universe expands, taking $\overline{g}(b) = g_0$, a constant of order one, will only overestimate the opacity. Similarly, following [1] in dropping the stimulated emission term will yield an upper limit to the free-free opacity. With $\epsilon = 1$, $\frac{h\nu_0}{kT_0} = 1$ when $\nu_0 \sim 10^{14}\ \mathrm{s}^{-1}$, so stimulated emission will only lead to a noticeable reduction in Σ_{ff} well below the optical. (Actually, methods similar to that employed in section 2.A can be employed to calculate this term, but as τ_{ff} will turn out to be insignificant even neglecting it there is no need to go into that here.)

With these approximations,

$$\Sigma_{\mathrm{ff}} \approx (4.6 \cdot 10^{-8}) g_0 \delta^2 \epsilon^{-\frac{1}{2}} h^4 \nu_0^{-3} \left(\frac{a_0}{a}\right)^2,$$

and thus

$$\begin{aligned} \tau_{\mathrm{ff}} &= 2\frac{\Sigma_0 c}{H_0} \\ &= 8.6 \cdot 10^{20} h^3 g_0 \delta^2 \epsilon^{-\frac{1}{2}} \nu_0^{-3}. \end{aligned} \tag{2.24}$$

Recalling that $\delta = \epsilon = 1$ seem likely physical values, and noting that $\delta^2\epsilon^{-\frac{1}{2}} \lesssim 10^2$ at worst, taking $h^3 g_0 \delta^2 \epsilon^{-\frac{1}{2}} = 1$ is not unreasonable for an order of magnitude estimate. Thus $\nu_0 \sim 10^7 \mathrm{s}^{-1}$ (long radio) is required to get $\tau_{\mathrm{ff}} \sim 1$. Since $\tau_{\mathrm{ff}} \propto \nu_0^{-3}$ it drops sharply for photons with present frequency above that. For instance, at 5000Å

$$\tau_{\mathrm{ff}} = g_0 \delta^2 \epsilon^{-\frac{1}{2}} 10^{-24},$$

and inverse bremsstrahlung is completely negligible.

The Far Future

Finally, I mention that Davies and Twamley [1] consider what happens if baryons decay in a long lived universe. Following the considerations of [42], they conclude that the positronium "atoms" which will form far in the future (when the universe is large) remain transparent to photons with present frequencies in the optical. This is because the redshifted photons haven't enough energy to cause transitions between adjacent Ps energy levels. Similarly, if in the nearer future the electrons and protons in the IGM recombine to form more neutral hydrogen, this will also be transparent at the considered frequencies.

3 Extragalactic Background Radiation in a Statistically Time Symmetric Universe

3.A Lower Limit to the Excess Optical EGBR

The goal of this section is to explain why, in a statistically time symmetric universe (such as one with the CPT-related boundary conditions discussed in section 1.A), the optical extragalactic background radiation should be at least twice that expected in a universe which is not time symmetric, and possibly considerably more. Thus, assuming consistency with the RTH (*i.e.* the predictive assumption that physics near either boundary condition is practically insensitive to the presence of the other boundary condition, *cf.* section 1.B), it is possible to discover *experimentally* whether our universe is time symmetric. Section 3.C compares this prediction with present observations, concluding that the minimal prediction is consistent with upper limits on the observed optical EGBR. However, better observations and modeling may soon challenge even this minimal prediction.

At optical wavelengths, the isotropic bath of radiation from sources outside our galaxy is believed to be due almost exclusively to galaxies on our past light cone [40, 43, 44, 45, are some good general references]. There is no other physically plausible source for this radiation. In a model universe with time symmetric boundary conditions, however, there must in addition be a significant quantity of radiation correlated with the time-reversed galaxies which will exist in the recollapsing era, far to our future [1, 3]. The reason for this is that light from our galaxies can propagate largely unabsorbed into the recollapsing phase no matter how close to open the universe is, as shown in [1] and in section 2. This light will eventually arrive on galaxies in the recollapsing phase, or, depending on its frequency, be absorbed in the time-reversed equivalent of one of the many high column density clouds (Lyman-limit clouds and damped Lyman-α systems) present in our early universe [40, 43, 46], in the intergalactic medium, or failing that, at the time-reversed equivalent of the surface of last scattering. This will appear to observers in the recontracting phase as emission by one of those sources sometime in their galaxy forming era. Since future galaxies, up to high time-reversed redshift, occupy only a small part of the sky seen by today's (on average) isotropically emitting galaxies, much of the light from the galaxies of the expanding phase will proceed past the recontracting era's galaxies. Thus most of this light will be absorbed in one of the other listed media. Because of the assumption of global homogeneity and isotropy, the light from the entire history of galaxies in the expanding phase will constitute an isotropic bath of radiation to observers at the time-reverse of the present epoch that is *in addition* to the light from the galaxies to *their* past. By time symmetry, there will be a similar contribution to our EGBR correlated with galaxies which will live in the recollapsing phase, over and above that due to galaxies on our past light cone. To us this radiation will appear to arise in isotropically distributed sources *other* than galaxies. This picture of a transparent, time symmetric universe is illustrated in figure 1.

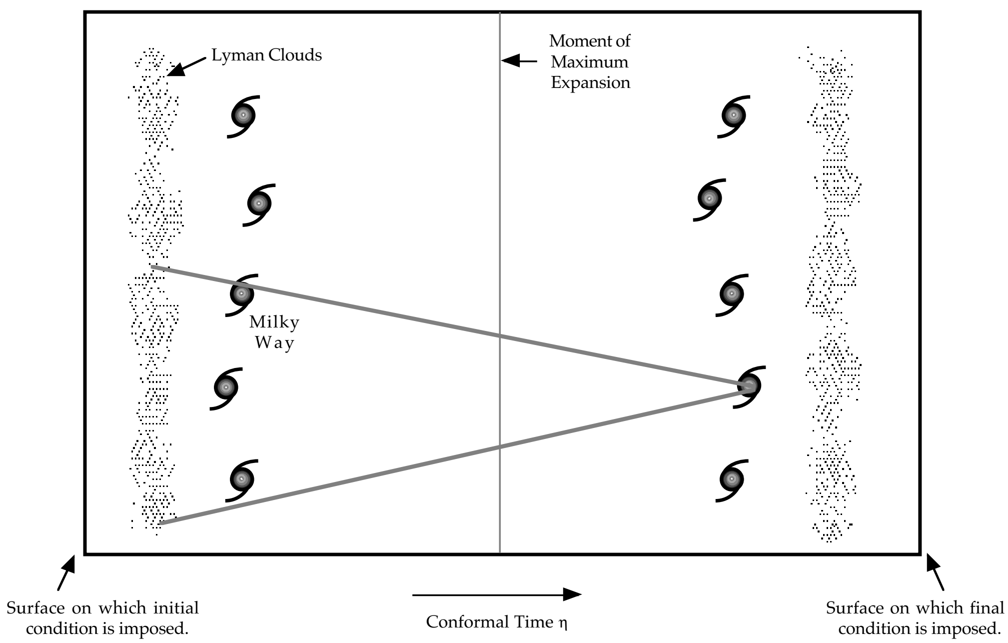

Figure 1: Schematic representation of the origin of the "excess" extragalactic background light correlated with the thermodynamically reversed galaxies of the recollapsing era. The model is a Friedmann-Robertson-Walker universe equipped with time symmetric boundary conditions requiring the universe to be smooth and in local thermodynamic equilibrium whenever it is small.

A lower limit to this excess background can be obtained by considering how much light galaxies to our past have emitted already (*cf.* section 3.C). According to observers at the time reverse of the present epoch, this background will (in the absence of interactions) retain its frequency spectrum and energy density because the size of the universe is the same. Thus, by time symmetry, at a *minimum* the predicted optical EGBR in a universe with time symmetric boundary conditions is twice that expected in a universe in which the thermodynamic arrow does not reverse. If much of the luminous matter in galaxies today will eventually be burned into radiation by processing in stars or galactic black holes, the total background radiation correlated with galaxies in the expanding phase could be several orders of magnitude larger, a precise prediction requiring a detailed understanding of the future course of galactic evolution [1]. Several other processes may also contribute significant excess backgrounds. These topics are discussed further below.

The Prediction

A number of points in the summary argument above require amplification. First, however, I summarize the *minimal*[13] predictions for the "excess" extragalactic background (*i.e.* radiation from non-galactic sources to our past that is correlated with time-reversed galaxies) in bands for which the future light cone is transparent:

- isotropy: the "future starlight" should appear in the comoving frame as an approximately isotropic background. This conclusion depends crucially on the assumed global validity of the cosmological principle.
- energy density: comparable to the present energy density in starlight due to the galaxies on our past light cone. This assumes the future light cone (FLC) is totally transparent.
- spectrum: similar to the present spectrum of the background starlight due to galaxies on our past light cone. Again, neglect of further emissions in the expanding phase makes this, by time symmetry, a lower limit in each band. This conclusion relies on the assumption of a transparent FLC in part to the extent that this implies a paucity of standard astrophysical mechanisms for distorting spectra.

Thus, at for instance optical frequencies, time symmetry requires an isotropic extragalactic background at least twice that due to galaxies on our past light cone alone.[14] The potentially far greater background predicted (by time symmetry) if further emissions in the expanding phase are accounted for is a subject taken up in the sequel.

Consistency with the RTH?

Before proceeding, a comment on the consistency of this picture is in order. As the "excess" radiation is correlated with the detailed histories of future galaxies, the transparency of the future light cone does not appear consistent with the predictive assumption (the RTH) that physics in the expanding era should be essentially independent of the specifics of what happens in the recontracting phase. At a minimum, if the model is to be at all believable it is legitimate to demand that the required radiation appears to us to arise in sources in a fashion consistent with known, or at least plausible, astrophysics. Thus it may be that given a transparent FLC, the only viable picture of a time symmetric universe is one in which the radiation correlated with future galaxies *"should" be there anyway, i.e.* be predicted also in some reasonable model of our universe which is *not* time symmetric, and consequently not be "excess" radiation at all, but merely optical radiation arising in non-galactic sources during (or before) the galaxy

[13] By "minimal" I mean the lower limit in each band provided by taking the integrated background of light from galaxies in the expanding era to be only that which has *already* been emitted up to the present epoch. In the absence of absorption, by time symmetry this is the minimum background at the present epoch that must be correlated with galaxies in the recontracting phase, as in the previous paragraph.

[14] To be totally accurate, the quantity of radiation absorbed or scattered into another band between the present epoch and its time reverse should be subtracted. However, the upper limit to the total FLC opacity (due to anticipated processes) computed in section 2 was of order 10^{-2}, mostly due to a liberal ("black galaxy") assessment of the rate of interception of photons by galaxies, and I will therefore neglect such losses. Further, it is worth remembering that processes like Thomson scattering do not destroy photons or change their frequency, but only scatter them. Thus mere scattering processes may introduce isotropically distributed (via the cosmological principle) fluctuations in the background, but not change its total energy. Similarly, line or dust absorption usually result in re-radiation of the absorbed photons, conserving the total energy in an isotropic background (if the size of the universe doesn't change much before the photons are re-radiated), if not the number of photons with a given energy.

forming era. On the basis of present knowledge this does not describe our universe. The presence of the radiation required by time symmetry and the transparency of the FLC appears to be in significant disagreement with what is known about our galaxy forming era, as will become apparent below.

Were it the case for our universe that non-galactic sources provided a significant component of the optical EGBR, the difficulties with time symmetric boundary conditions would from a *practical* point of view be less severe. It is true that the non-galactic sources emitting the additional isotropic background would have to do so in just such a way that the radiation contain the correct spatial and spectral correlations to converge on future galaxies at the appropriate rate. This implies a distressingly detailed connection between the expanding and recontracting phases. However, if the emission rate and spectrum were close to that expected on the basis of conventional considerations these correlations (enforced by the time symmetric boundary conditions) would likely be wholly unobservable in practice, existing over regions that are not causally connected until radiation from them converges onto a future galaxy [1], and thus not visible to local coarse grainings (observers) in the expanding era. In any event, the meaning of the transparency of the FLC is that starlight is by no means a "short relaxation time process." Of course, on the basis of the models discussed in section 1.B, perhaps the conclusion to draw from this apparent inconsistency between the RTH and the transparency of the FLC should rather be, that physical histories would unfold in a fashion quite different from that in a universe in which $\rho_\omega = 1$, namely, in such a way that such detailed correlations would never be required in the first place. The very formation of stars might be suppressed (*cf.* section 4). Be that as it may, to the extent that the universe to our past is well understood, there are *no* sources that could plausibly be responsible for an isotropic optical background comparable to that produced by galaxies. Such an additional background, required in a transparent, time symmetric universe, requires significant, observable deviations from established astrophysics. This is in direct contradiction with the RTH. Thus the entire structure in which an additional background is predicted appears to be both internally inconsistent (in that it is inconsistent with the postulate which allows predictions to be made in the first place), and, completely apart from observations of the EGBR discussed in section 3.C, inconsistent with what is known about our galaxy forming era. This should be taken as a strong argument that our universe does not possess time symmetric boundary conditions. Nevertheless, in order to arrive at this conclusion it is necessary to pursue the consequences of assuming the consistency of the model. The situation may be stated thus: *either* our universe is not time symmetric, *or* there is an unexpected contribution to the optical EGBR due to non-galactic sources to our past (and there are indeed detailed correlations between the expanding and recontracting eras), *or* perhaps our future light cone is not transparent after all. This latter possibility, perhaps related to the considerable uncertainty regarding the state of the universe when it is large, seems the last resort for a consistent time symmetric model of our universe.

3.B Amplifications

It is now appropriate to justify further some of the points made in arriving at the prediction of an excess contribution to the EGBR. Claims requiring elaboration include: i) most of the light from the expanding era's galaxies won't be absorbed by the galaxies of the recontracting phase, and *vice-versa*; ii) it will therefore be absorbed by something else, and this is inconsistent with the early universe as presently understood; iii) a detailed understanding of the old age and death of galaxies, as well as other processes when the universe is large, may lead to a predicted EGBR in a time symmetric universe that is orders of magnitude larger than the minimal prediction outlined above. I deal with these questions in turn.

The "Excess" EGBR is Not Associated with Galaxies to Our Past

A photon escaping our galaxy is unlikely to encounter another galaxy before it reaches the time reverse of the present epoch. In fact, as shown in section 2, galaxies between the present epoch and its time reversed equivalent subtend, at most, roughly a mere $2 \times .01 = 2\%$ of the sky (2.21) (neglecting curvature and clumping.) In light of the present lack of detailed information about our galaxy forming era (and via time symmetry its time-reverse), a photon's fate after that is more difficult to determine. A straightforward extrapolation of the results of section 2 (or *cf.* *e.g.* section 13 of Peebles [40]) shows that the optical depth for encounters with galaxies of the same size and numbers as today is $\tau \sim .01(1+z)^{\frac{3}{2}}$ between a redshift of z and today. Again this neglects curvature (hence overestimating τ) and clumping (which now underestimates τ.) Assuming the bright parts of galaxies form at $z \sim 5$, this gives only $\tau \sim .14$, and the sky isn't covered with them until $z \sim 20$. This however is roughly at the upper limit on how old galaxies are thought to be. On the other hand, examination of quasar spectra (out to $z \sim 5$) show that most lines of sight pass through many clouds of high column densities of hydrogen called Lyman-α forest clouds and, at higher densities, damped Lyman-α systems. (Peebles [40] is a useful entry point on all of these matters, as is [43]. [46] are the proceedings of a recent conference concerned with these Lyman systems.) The highest density clouds may be young galaxies, but if so galaxies were more diffuse in the past as the observed rate of interception of an arbitrary line of sight with these clouds is a factor of a few or more greater than that based on the assumption that galaxy sizes are constant. (Obviously, this would not be too surprising.) For instance, for the densest clouds Peebles [40, section 23] relates the approximate formula

$$\frac{dN}{dz} = 0.3\,{\Sigma_{20}}^{-0.46}$$

for the observed interception rate per unit redshift of a line of sight with a cloud of column density greater than or equal to Σ_{20} (in units of $10^{20}\,\mathrm{cm}^{-2}$), in a range of redshifts about $z = 3$. For Lyman-α forest clouds, $\Sigma \gtrsim 10^{14}\,\mathrm{cm}^{-2}$, the interception rate is considerably higher. (For some models see [47, 48].) Thus an arbitrary line of sight arriving on our galaxy from a redshift of five, say, is likely to have passed through at least one cloud of column density comparable to a galaxy, and certainly many clouds of lower density. What might this mean for time symmetry?

(For specificity I shall concentrate on photons which are optical today, say around 5000Å. This band was chosen because at these wavelengths we have the luxury of the coincidence of decent observations, relatively well understood theoretical predictions for the background due to galaxies, the absence of other plausible sources for significant contributions, and a respectable understanding of the intergalactic opacity, including in particular some confidence that the future light cone is transparent.)

Photons at 5000Å today are at the Lyman limit (912Å) at $z \approx 4.5$, and so are ionizing before that. At these redshifts the bounds on the amount of smoothly distributed neutral hydrogen (determined by independent measures such as the Gunn-Peterson test [40]) are very low (*cf.* section 2.B), presumably because that part of the hydrogen formed at recombination which had not been swept into forming galaxies was ionized by their radiation. Before the galactic engines condensed and heated up, however, this neutral hydrogen would have been very opaque to ionizing radiation. Similarly, near $z \sim 4$ Lyman-limit clouds with $\Sigma \gtrsim 10^{17}\,\mathrm{cm}^{-2}$ are opaque at these frequencies. The upshot is that most photons from our galaxies which are optical today will make it well past the time reverse of the present epoch, likely ending up in the (time-reversed) L-α forest or in a young (to time reversed observers!) galaxy by $\tilde{z} \sim 4$. (Here $\tilde{z}$ is the epoch corresponding to the time-reverse of redshift z.) The very few that survive longer must be absorbed in the sea of neutral hydrogen between $\tilde{z} = 0$ and (their) recombination epoch, $\tilde{z} \sim 1000$.

Now, the important point is that on average, galaxies radiate isotropically into the full 4π of sky available to them. The lesson of the previous paragraph is that most lines of sight from galaxies in the expanding phase will not encounter a high column density cloud until a fairly high time-reversed redshift, $\tilde{z} \sim$ few, at which point many lines of sight probably *will* intersect one of these proto-galaxies or their more diffuse halos. If most photons from our galaxies have not been absorbed by this point, *this is not consistent with time symmetry*: the rate of emission of (what is today) optical radiation by stars in galaxies could not be time symmetric if the light of the entire history of galaxies in the expanding phase ends up only on the galaxies of the recollapsing phase at high $\tilde{z}$ (due consideration of redshifting effects is implied, of course.) Put another way, time symmetry requires the specific energy density in the backround radiation to be time symmetric. Thus the emission rate in the expanding era must equal (what we would call) the absorption rate in the recontracting phase. If stars in galaxies were exclusively both the sources (in the expanding phase) and sinks (as we would call them in the recontracting phase) of this radiation, galactic luminosities in the expanding phase would have to track the falling rate of absorption due to photon "collisions" with galaxies. This is absurd. At the present epoch, for example, *at all frequencies* galaxies would (by time symmetry) have to be absorbing the diffuse EGBR (a rate for which the upper limit is determined entirely by geometry in the "black galaxy" approximation) at the same rate as their stars were radiating (a rate that, in a time symmetric universe which resembles our own, one expects to be mostly determined by conventional physics.)[15] That is, stars would be in radiative equilibrium with the sky! This may be called the "no Olber's Paradox" argument against the notion that a single class of localized objects could be exclusively responsible for the EGBR in a transparent universe equipped with time symmetric boundary conditions. (It might be thought that this problem would be solved if the time symmetric boundary conditions lead galaxies to radiate preferentially in those directions in which future galaxies lie. This is not a viable solution, because as noted above, only a small fraction of the sky is subtended by future galaxies up to high time reversed redshift. The deviations from isotropic emission would be dramatic.)

Thus, the option consistent with time symmetry is that most galactic photons which are optical today will ultimately be absorbed in the many (by time symmetry) time-reversed Lyman-α forest clouds or Lyman-limit clouds believed to dwell between galaxies, and not in the stars of the time-reversed galaxies themselves.[16] Fortunately for the notion of time symmetry this indeed appears to be the case. Careful studies of the opacity associated with Lyman systems [49, 50], indicates, within the bounds of our rather limited knowledge, that the light cone between $z = 4.5$ and $z = 0$ is essentially totally opaque to radiation that is 5000Å at $z = 0$, and that this is due largely to Lyman clouds near $z \sim 4$ and in the middle range of observed column densities, $\Sigma \sim 10^{16-17}\,\mathrm{cm}^{-2}$ or so. (To be honest, it must be admitted that hard data on just such clouds is very limited [51, 50].)

We have now arrived at a terrible conundrum for the notion of time symmetry. Even if one is willing to accept the amazingly detailed correlations between the expanding and recontracting eras that reconciling a transparent future light cone with time symmetry requires, and even if the "excess" radiation correlated with the galaxies of the recollapsing era were to be observed, this picture is incompatible with what little is known about the physical properties of the Lyman-α forest. Recalling the minimal prediction above for the excess background required by time symmetry, the prediction is that the Lyman-α forest has produced an amount of radiation at least comparable to that produced by the galaxies to our past. There is no mechanism by which this is reasonable. *There is no energy source to provide this amount of radiation.* More prosaically, the hydrogen plasma in which the clouds largely consist is observed (via determination of the line shape, for example) to be at kinetic temperatures of order $10^{4-5}K$, heated by quasars and young galaxies [52, 53]. Thermal bremsstrahlung is notoriously inefficient, and line radiation at these temperatures is certainly insufficient to compete with nuclear star burning in galaxies! At for instance 5000Å today, essentially *no* radiation is expected from forest clouds at all, let alone an amount comparable to that generated by galaxies. Remembering that by redshifts of 4.5 the Lyman forest is essentially totally opaque shortward of 5000Å (observed) [50], it might have been imagined that an early generation of galaxies veiled by the forest heated up the clouds sufficiently for them to re-radiate the isotropic background radiation required by time symmetry. While it is true that quasars and such are likely sources of heat for these clouds [53, for example], aside from the considerable difficulties in getting the re-radiated spectrum to resemble that of galaxies, the observed temperatures of the clouds are entirely too low to be compatible with the *minimum* amount of energy emission in the bands required.

(A related restriction arises from present day observations of cosmological metallicities, which constrain the amount of star burning allowed to our past. If observed discrete sources came close to accounting for the required quantity of heavy elements, the contribution of a class of objects veiled completely by the Lyman forest would be constrained irrespective of observations of the EGBR. However, at present direct galaxy counts only provide about 10% of the current upper limits on the extragalactic background light [54] (*cf.* section 3.C), the rest conventionally thought to arise in unresolvable galactic sources. Consequently, correlating formation of the heavy elements with observed discrete sources does not at present provide a good test of time symmetry. At any rate, such a test is likely to be a less definitive constraint on time symmetry because it is possible that a portion of the radiation lighting the Lyman forest from high redshift is not due to star burning, but to accretion onto supermassive black

[15] This is illustrated in the appendix with a simplified model. Related considerations may be used to put detailed constraints on the self-consistency of time symmetry, but I do not address that any further beyond the appendix. The essential point has already been made.

[16] This may be disappointing. A nice picture of a time symmetric universe might have photons from our galaxies arriving at time-reversed galaxies in the recollapsing era, appearing as their emissions. Even ignoring the highly detailed correlations between the expanding and recollapsing phases this would imply, the scheme could only work if radiation could be removed by galaxies in the recollapsing phase at the same rate it is emitted in the expanding. As noted, for isotropically emitting sources this is forbidden by time symmetry of the emission rate and geometry.

holes at the centers of primordial galaxies. Thus the best observational test is the most direct one, comparison of the observed EGBR with the contribution expected from galaxies.)

The possibility that somehow the excess radiation does *not* come from the Lyman-α forest, but somehow shines through from other isotropically distributed sources even further in the past, is hardly more appealing. Familiar physics tells us that the forest is totally opaque to radiation that is 5000Å at $z = 0$. The conclusion had better be that the universe is not time symmetric, rather than that time symmetry engineers a clear path only for those photons correlated with galaxies in the recollapsing epoch (and not, say, the light from quasars.) Moreover, even if that were the case, analagous difficulties apply to the vast sea of neutral hydrogen that existed after recombination, totally opaque to ionizing radiation, and again to the highly opaque plasma which constituted the universe *before* recombination. It is possible to conjure progressively more exotic scenarios which save time symmetry by placing the onus on very special boundary conditions which engineer such rescues, but this is not the way to do physics. The only *reasonable* way time symmetry could be rescued would be if it were discovered that for reasons unanticipated here, the future light cone were not transparent after all, thus obviating the need for an excess background radiation with all its attendant difficulties. Otherwise, it is more reasonable to conclude that a universe with time symmetric boundary conditions would not resemble the one in which we actually live.

Beyond the Minimal Prediction

Now that we have seen what kind of trouble time symmetry can get into with only the *minimal* required excess background radiation, it is time to make the problems worse. The background radiation correlated with the galaxies of the recollapsing era was bounded from below, via time symmetry, by including only the radiation that has been emitted by the galaxies to our past. But as our stars continue to burn, if the future light cone is indeed transparent it is possible a great deal more radiation will survive into the recollapsing era [1, 3]. How much more? To get an idea of what's possible it is necessary to know both what fraction of the baryons left in galaxies will be eventually be burned into starlight, and when. For a rough upper bound, assume that *all* of the matter in galaxies today, including the apparently substantial dark halos (determined by dynamical methods to contribute roughly $\Omega_{\rm gal} \sim .1$), will eventually be burned into radiation. To get a rough lower bound, assume that only the observed luminous matter ($\Omega_{\rm lum} \sim .004$) will participate significantly, and that only a characteristic fraction of about 4% of *that* will not end up in remnants (Jupiters, neutron stars, white dwarfs, brown dwarfs, black holes, *etc.*) To overestimate the energy density of this background at $\tilde{z} = 0$, assume that all of this energy is released in a sudden burst at some redshift $z_e (< 0)$. Then by time symmetry, further star burning will yield a background of radiation correlated with time-reversed galaxies (expressed as a fraction of the critical density and scaled to $z = 0$) somewhere in the range

$$(1 + z_e)^{-1} 10^{-6} \lesssim \Omega_{\rm burn} \lesssim (1 + z_e)^{-1} 10^{-3}.$$

(Here I have used the fact that the mass fraction released in nuclear burning as electromagnetic radiation is .007.) When $(1 + z_e)^{-1} \sim 1$ the upper limit is two orders of magnitude more than is in the CMBR today and three orders of magnitude more than present observational upper limits on a diffuse optical extragalactic background (*cf.* section 3.C). The lower bound, however, is comparable to the amount of radiation that has already been emitted by galaxies. Thus if the lower bound obtains, the prediction for the optical EGBR in a time symmetric universe is only of order three times that due to the galaxies to our past (if the excess background inferred from continued star burning is not distributed over many decades in frequency, and if most of this burning occurs near $z(\tilde{z}) = 0$.) As will be seen in section 3.C, this may still be consistent with present observational upper limits. On the other hand, if something closer to the upper limit obtains this is a clear death blow to time symmetry. A more precise prediction is clearly of interest. This would entail acquiring a detailed understanding of further galactic evolution, integrating over future emissions with due attention to the epoch at which radiation of a given frequency is emitted. (Naturally, this is the same exercise one performs in estimating the EGBR due to galaxies to our past [43].)

Some idea of the possible blueshift ($(1 + z_e)^{-1}$) involved comes from estimating how long it will take our galaxies to burn out. This should not be more than a factor of a few greater than the lifetime of the longest lived stars, so a reasonable ballpark figure is to assume that galaxies will live for only another ten billion years or so. For convenience, assume that galaxies will become dark by $t = nt_0$ for some n, where t_0 is the present age of the universe. To overestimate the blueshift at this time, assume the universe is flat, so that

$$(1 + z_e)^{-1} = (t/t_0)^{\frac{2}{3}} = n^{\frac{2}{3}}.$$

For reasonable n's this does not amount to a large (in order of magnitude) transfer of energy to the radiation from cosmological recontraction.

Additional Sources of "Excess" EGBR and the Far Future

In a similar fashion to continued burning of our stars, any isotropic background produced to our future might by time symmetry be expected to imply an additional contribution to the EGBR in an appropriately blueshifted band. For instance, even if continued star burning does not (by time symmetry) yield a background in contradiction with observations of the EGBR, it is possible that accretion onto the supermassive black holes likely to form at the centers of many galaxies could ultimately yield a quantity of radiation dramatically in excess of that from star burning alone.[17] In the absence of detailed information about such possibilities it is perhaps sufficient to note that ignoring possible additional contributions leads to a lower limit on the EGBR correlated with sources in the recontracting era, and I will therefore not consider them.

There is one worrying aspect, however. As discussed in some detail by Page and McKee [42] for an approximately $k = 0$ universe, and commented on in a related context in section 4.A, if baryons decay then considerable photons may be produced by for instance the pair annihilation of the resulting electrons and positrons. Should not this, by time symmetry, yield a further contribution to the EGBR? The answer may well be yes, but there is a possible mechanism which avoids this conclusion. Somehow, with CPT symmetric boundary conditions, the density of baryons must be CPT symmetric. Therefore either baryons do not decay, or they are re-created[18] in precisely correlated collisions. (In the absence of a final boundary condition, the interaction rate would be too low for (anti-)baryon recombination to occur naturally.) The latter (boundary condition enforced) possibility appears extraordinary, but if baryon decay occurs in a universe with CPT symmetric boundary conditions, it could be argued that the best electrons and photons for the job would be just those created during baryon decay in the expanding phase, thereby removing this photon background. The "no Olber's Paradox" argument, that most of an isotropically emitting source's light must end up in some homogeneous medium, and not, if time symmetry is to be preserved, equivalent time-reversed point sources, may not apply here if matter is relatively homogeneously distributed when the universe is large. Baryon decay *might* smooth out inhomogeneities somewhat before the resulting electrons and positrons annihilate. (This requires the kinetic energies of the decay products to be comparable to the gravitational binding energy of the relevant inhomogeneity.) Then the picture is no longer necessarily of localized sources emitting into 4π, but of a more homogeneous photon-producing background that might cover enough of the sky to more reasonably secrete the required correlations for reconstruction of more massive particles in the recontracting phase. Nevertheless the extreme awkwardness of this scenario is not encouraging. The former possibility, clearly more palatable, is that baryons do not decay significantly either because Ω is not so near one after all that they have time enough to do so, or because the presence of the final boundary condition suppresses it. Either way, in this (possibly desperate) picture there is no additional background due to decaying baryons. A very similar question relates to the enormous number of particles produced in the last stages of black hole evaporation. This time, however, the objection that our black holes cover only a small portion of the recontracting era's sky, and consequently their isotropic emissions could not do the job of forming the white holes of the recontracting era (black holes to observers there) time symmetrically, would seem to be forceful. Thus if the universe is indeed very long-lived, black hole evaporation may well require yet an additional observable background. This may not be such a serious

[17] I owe this suggestion to R. Antonucci.

[18] Note that in the former case CPT-symmetry requires that the observed matter-antimatter asymmetry inside the horizon does not persist at larger scales. In the latter case, *if* matter dominates homogeneously in the expanding era, then antimatter must dominate homogeneously in the recollapsing phase. Further discussion of CP-violation in T- and CPT-symmetric universes may be found in [3].

difficulty if Ω is not very close to one, however, as the time scales for the evaporation of galactic-scale black holes are quite immense. Further discussion of black holes in time symmetric cosmologies may be had in [10, 15, 35].

One last point regarding the predictions described in this section needs to be made. Clearly, a loose end which could dramatically change the conclusions is the condition of matter in the universe when it is very large. This is uncertain territory, not the least because that is the era in a statistically time symmetric universe when the thermodynamic arrow must begin rolling over. Neglecting this confusing complication (reasonable for some purposes as many interactions are most significant when the universe is small), there is not a great deal known about what the far future should look like [55, 56, 57, 58, 59, 42]. The study of Page and McKee [42] gives the most detailed picture in the case of a flat universe. As mentioned at the end of section 2.B, Davies and Twamley [1] find from this work that interactions of optical (at $z = 0$) backgrounds with the electrons produced by baryon decay do not appear to be significant, primarily due to their diffuseness. On the other hand, if supermassive black holes (or any large gravitational inhomogeneities) appear, interactions with them may induce anisotropies in the future starlight. However, clumping only decreases the probability a line of sight intersects a matter distribution. Therefore large overdensities probably never subtend enough solid angle to interfere with most lines of sight to the recollapsing era unless gravitational collapse proceeds to the point where it dramatically alters homogeneity and isotropy on the largest scales. Because collapse is rather strongly constrained by time symmetry (*cf.* section 4.A) I will not consider this possibility. Thus, insofar as the prediction of an "excess" background radiation correlated with galaxies in the recollapsing era is concerned, the state of the universe when it is large would does not obviously play a substantial role. Nevertheless, given the manifold difficulties cited, the sentiment expressed above is that the best hope a time symmetric model has of providing a realistic description of our universe is that some unforseen mechanism makes the future light cone opaque after all.

Summary

To summarize, because our future light cone is transparent, neglecting starburning to our future and considering only the contribution to the EGBR from stars in our past provides an estimate of the total EGBR correlated with galaxies in the recollapsing era that is actually a lower limit on it. As mechanisms for distorting the spectrum generically become less important as the universe expands (barring unforseen effects in the far future), it is reasonable to take models for the present EGBR due to stars in our past as a minimal estimate of the isotropic background of starlight that will make its way to the recollapsing era. By time symmetry we can expect that at the same scale factor in the recollapsing era similar (but time-reversed) conditions obtain. As argued above, by time symmetry and geometry this "future starlight" must appear to us as an additional background emanating from homogeneously distributed sources to our past *other* than galaxies. Therefore, if the universe has time symmetric boundary conditions which (more or less) reproduce familiar physics when the universe is small, and our future light cone is transparent, the optical extragalactic background radiation should be at least twice that expected to be due to stars in our past alone, and possesses a similar spectrum. If a considerable portion of the matter presently in galaxies will be burned into radiation in our future, by time symmetry the expected background is potentially much larger, and observations of the EGBR may already be flatly incompatible with observations. Nevertheless, in the next section I shall be conservative and stick with the minimal prediction in order to see how it jibes with observations.

3.C Models and Observations of the Optical EGBR

At optical wavelengths, it is generally believed that the isotropic background of radiation from extragalactic sources is due entirely to the galaxies on our past light cone [43, 44, 45]. As shown in the previous section, if our universe is time symmetric there must in addition be a significant contribution correlated with the galaxies of the recollapsing era which arises, not in galaxies, but in some homogeneously distributed medium, say for instance the Lyman clouds. The apparent inconsistency of this prediction with what is known about the forest clouds has been discussed above, and may be taken as an argument that our universe is not time symmetric. In this section judgement will be suspended, and the prediction of an "excess" EGBR at least comparable to, but over and above, that due to galaxies to our past will be compared with experiment. The conclusion will be that current data are still consistent with time symmetry *if* our galaxies will not, in the time left before they die, emit a quantity of radiation that is considerably greater than that which they already have.

A useful resource on both the topics of this section is [43].

Tyson [54] has computed how much of the optical extragalactic background is accounted for by resolvable galaxies, concluding that known discrete sources contribute

$$\nu i_\nu \sim 3 \cdot 10^{-6} \, \mathrm{erg\ cm^{-2}\ s^{-1}\ ster^{-1}} \tag{3.1}$$

at 4500Å. However, because very distant galaxies contribute most of the background radiation it is believed that unresolvable sources provide a significant portion of the EGBR. At present it is not possible to directly identify this radiation as galactic in origin. However, as understanding of galactic evolution grows so does the ability to model the optical extragalactic background due to galaxies. These predictions naturally depend on the adopted evolutionary models, what classes of objects are considered, the cosmological model, and so on. As representative samples I quote the results of Code and Welch [60] for a flat universe in which all galaxies evolve,

$$\nu i_\nu \sim 8 \cdot 10^{-6} \, \mathrm{erg\ cm^{-2}\ s^{-1}\ ster^{-1}} \tag{3.2}$$

at 5000Å, and of Cole *et al.* [61] for a similar scenario,

$$\nu i_\nu \sim 3 \cdot 10^{-6} \, \mathrm{erg\ cm^{-2}\ s^{-1}\ ster^{-1}}, \tag{3.3}$$

also at 5000Å. These figures are to be compared with the results of (extraordinarily difficult) observations. As surveyed by Mattila [62], they give at 5000Å an upper limit of

$$\nu i_\nu \lesssim 2 \cdot 10^{-5} \, \mathrm{erg\ cm^{-2}\ s^{-1}\ ster^{-1}}. \tag{3.4}$$

As far as I am aware, there has been no direct detection of an optical radiation background of extragalactic origin. This upper limit represents what is left after what can be accounted for in local sources is removed.

Comparing these results, it is clear that if current models of galactic evolution are reliable, present observations of the extragalactic background radiation leave room for a contribution from non-galactic sources that is comparable to the galactic contribution, but not a great deal more. These observations therefore constrain the possibility that our universe is time symmetric. If believable models indicate that further galactic emissions compete with what has been emitted so far, time symmetry could already be incompatible with experiment. A direct detection of the extragalactic background radiation, or even just a better upper limit, could rule out time symmetry on *experimental* grounds soon.[19] (The ideal observational situation would be convergence of all-sky photometry and direct HST galaxy counts, allowing one to dispense with models completely.)

4 Further Difficulties with Time Symmetry

In this section I comment on some issues of a more theoretical nature which must be faced in any attempt to construct a believable model of a time symmetric universe. Among other questions, in such a universe the difficulties with incorporating realistic gravitational collapse, and in deriving the fact that radiation is retarded, appear to be considerable.

4.A Gravitational Collapse

A careful account of the growth of gravitational inhomogeneities from the very smooth conditions when the universe was small is clearly of fundamental importance in any model of the universe, time symmetric

[19] To be more careful, if direct HST galaxy counts, or reliable models of the (extra-)galactic contribution closely agree with the observations, the justifiable conclusion is that *if* our universe is time symmetric, then for some unknown reason our future light cone is not transparent.

or not, not the least because it appears to be the essential origin of the thermodynamic arrow of time[20] from which the other apparent time arrows are thought to flow [12, 9]. However, if matter in a closed universe is to be smooth at both epochs of small scale factor then it is incumbent to demonstrate that Einstein's equations admit solutions in which an initially smooth universe can develop interesting (non-linear) inhomogeneities such as galaxies which eventually smooth out again as the universe recollapses. This is because the universe is certainly in a quasiclassical domain now, and if it is assumed to remain so whenever the scale factor is large classical general relativity must apply. Laflamme [36] has shown that in the linear regime there are essentially no perturbations which are regular, small, and growing away from both ends of a closed FRW universe, so that in order to be small at both ends a linear perturbation must be too small to ever become non-linear. But that is not really the point. Interesting perturbations must go non-linear, and there is still no proof of which I am aware that perturbations which go non-linear cannot be matched in the non-linear regime so as to allow solutions which are small near both singularities. Put differently, what is required is something like a proof that Weyl curvature must increase (*cf.* [15, 35]), *i.e.* that given some suitable energy conditions the evolution of gravitational inhomogeneity must be monotonic even in the absence of trapped surfaces, except possibly on a set of initial data of measure zero. While perhaps plausible given the attractive nature of gravity, proof has not been forthcoming.

(It is important for present purposes that genericity conditions on the initial data are not a central part of such a proof, for physically realistic solutions which meet the time symmetric boundary conditions must describe processes in the recollapsing era which from our point of view would look like galaxies disassembling themselves. Reducing such a solution to data on one spacelike hypersurface at, say, maximum expansion, said data will be highly specialized relative to solutions with galaxies which do not behave so unfamiliarly. If such solutions with physically interesting inhomogeneities do exist, the real question here is whether they are generic *according to the measure defined by the two-time boundary conditions.* Since it ought to be possible to treat this problem classically, in principle this measure is straightforward to construct. The practical difficulty arises in evaluating the generic behaviour of solutions once they go non-linear. My own view is that it is highly likely that such solutions remain exceedingly improbable according to a measure defined by a *generic* set of (statistical) boundary conditions requiring the universe to be smooth when small. As noted, Laflamme [36] has already shown that when the initial and final states are required to be smooth, the growth of inhomogeneity is suppressed if only linear perturbations are considered. Unless boundary conditions with very special correlations built in are imposed, probable solutions should resemble their smooth initial and final states throughout the course of their evolution, never developing physically interesting inhomogeneities.[21]

Note the concern here is not with occurrences which would be deemed unlikely in a universe with an initial condition only, but occur in a time symmetric universe because of the "fate" represented by the final boundary condition, but with occurrences which are unlikely *even in a universe with (generic) time symmetric boundary conditions.*)

A related question concerns collapsed objects in a time symmetric universe. Page and McKee [42] have studied the far future of a $k = 0$ FRW universe under the assumption that baryons decay but electrons are stable. Assuming insensitivity to a final boundary condition their conclusions should have some relevance to the period before maximum expansion in the only slightly over-closed (and hence very long-lived) model universes that have mostly been considered here. As discussed in section 3.B, if the universe is very long lived it might be imagined that the decay of baryons and subsequent annihilation of the produced electrons and positrons could smooth out inhomogeneities, and also tend to destroy detailed information about the gravitational history of the expanding phase (by eliminating compact objects such as neutron stars, for instance.) Thus, even though interactions are unlikely to thermalize matter and radiation when the universe is very large [42] (*cf.* section 2), there may be an analagous information loss via the quantum decay of baryons which could serve a similar function. (For a completely different idea about why quantum mechanics may effectively decouple the expanding and

[20] For examples of concrete calculations connecting the growth of gravitational inhomogeneities with the emergence of a thermodynamic arrow see [63, 7, 18].

[21] One possible out is Schulman's observation that systems which exhibit chaos, as general relativity does, may be less restricted in the varieties of their behaviour by boundary conditions at two times than are systems with linear dynamics [30]. This substantially unstudied possibility would obviously never emerge from Laflamme's linear analysis.

recollapsing eras, see [8, 9, 10, 11].) In any case, if there is no mechanism to eliminate collapsed objects before the time of maximum expansion, then the collapsed objects of the expanding phase are the same as the collapsed objects of the recontracting phase, implying detailed correlations between the expanding and recontracting era histories of these objects which might lead to difficulties of consistency with the RTH.

A particular complication is that it is fairly certain that black holes exist, and that more will form as inhomogeneity grows. The only way to eliminate a black hole is to allow it to evaporate, yet the estimates of Page and Mckee indicate that it is more likely for black holes to coalesce into ever bigger holes unless for some reason (a final boundary condition?) there is a maximum mass to the black holes which form, in which case they may have time enough to evaporate (though this requires Ω to be *exceedingly* close to one.) In fact, it may be imperative for a time symmetric scenario that black holes evaporate, else somehow they would have to turn into the white holes of the recollapsing era (black holes to observers there.) This is because we do not observe white holes today [15, 35]. (A related observation is that in order for the universe to be smooth whenever it is small, black/white hole singularities cannot arise [10].) Here the evaporation of black holes before maximum expansion would be enforced by the time symmetric boundary conditions selecting out only those histories for which there are no white holes in the expanding era and *mutatis mutandis* for the recollapsing era.[22] On the other hand, if evaporating black holes leave remnants they too must be worked into the picture. Again, if the results of the stochastic models with two-time low entropy boundary conditions discussed above are to be taken seriously, the conclusion should probably be that boundary conditions requiring homogeneity when the universe is small suppress histories in which significant gravitational collapse occurs by assigning low probabilities to histories with fluctuations that will go non-linear. It hardly needs emphasizing that all of these considerations are tentative, and greater clarity would be welcome.

4.B The Retardation of Radiation

Besides gravitational considerations, radiation which connects the expanding and recollapsing eras provides another example of a physical process which samples conditions near both boundary conditions [1]. While gravitational radiation and neutrinos are highly penetrating and are likely to provide such a bridge, in neither case are we yet capable of both effectively observing, and accurately predicting, what is expected from sources to our past. Therefore the primary focus of this investigation has been electromagnetic radiation. Above it was confirmed that modulo the obviously substantial uncertainty regarding the condition of the universe when it is large, even electromagnetic radiation is likely to penetrate to the recollapsing era. Section 3 was concerned with one relatively prosaic consequence of this prediction if our universe possesses time symmetric boundary conditions. Here I comment briefly on another.

Maxwell's equations, the dynamical laws governing electromagnetic radiation, are time symmetric. It is generally believed that the manifest asymmetry in time of radiation *phenomena*, that is, that (in the absence of source-free fields) observations are described by retarded solutions rather than advanced, is ascribable fundamentally to the thermodynamic arrow of time without additional hypotheses. (For a contemporary review see [9].) However, if our universe possesses time symmetric boundary conditions then near the big bang the thermodynamic arrow of entropy increase runs oppositely to that near the big crunch. Since radiation can connect the expanding and recollapsing eras, the past light cone of an accelerating charge in the expanding era ends up in matter for which the entropy is increasing, while its future light cone terminates in matter for which entropy is supposed to be *decreasing*. If the charge radiates into its future light cone this implies detailed correlations in this matter with the motion of the charge which are incompatible with the supposed entropy decrease there (entropy increase to time reversed observers), although it is true that these correlations are causally disconnected to time-reversed observers, and consequently invisible to *local* coarse grainings defining a local notion of entropy for such observers. This state of affairs makes it difficult to decide whether radiation from an accelerating charge (if its radiation can escape into intergalactic space) should be retarded (from the perspective of observers in the expanding era) or advanced or some mixture of the two. The conditions under which the radiation arrow is usually derived from the thermodynamic arrow of surrounding matter do not hold. (Notice how this situation is reminiscent of the requirements necessary to derive retardation of radiation in the

[22] For more on black holes in time symmetric universes, see the discussion of Zeh [10].

Wheeler-Feynman "absorber theory" of electrodynamic phenomena [64].) Hence the ability of radiation to connect the expanding and recollapsing epochs brings into question the self-consistency of assuming time symmetric boundary conditions on our universe together with "physics as usual" (here meaning radiation which would be described as retarded by observers in both the expanding and recollapsing eras) near either end. The retardation of radiation is another important example of a physical prediction which would be expected to be very different in a universe with time symmetric boundary conditions than in one without. Once again, if the results of the simple stochastic models are generally applicable, the retardation of radiation should no longer be a prediction in such a universe.[23]

To summarize this section, consideration of gravitational collapse and radiation phenomena reveals that construction of a model universe with time symmetric boundary conditions which resembles our own may be a difficult task indeed. There are strong suggestions that a model with time symmetric boundary conditions which mimic our own early universe would behave nothing like the universe in which we live. Such a model would most likely predict a universe which remained smooth throughout the course of its evolution, with coupled matter components consequently remaining in the quasi-static "equilibrium" appropriate to a dynamic universe.

5 Summation

In spite of the oft-expressed intuitive misgivings regarding the possibility that our universe might be time symmetric [65, 12, 15, for example], it has generally been felt that if sufficiently long-lived, there might be no way to tell the difference between a time symmetric and time asymmetric universe. Building on suggestions of Cocke, Schulman, Davies, and Gell-Mann and Hartle (among others), this work has explored in some detail one physical process which, happily, belies this feeling: no matter how long our universe will live, the time symmetry of the universe implies that the extragalactic background radiation be *at least* twice that due to the galaxies to our past. This is essentially due to the fact that light can propagate unabsorbed from the present epoch all the way to the recollapsing era. Moreover, geometry and time symmetry requires this "excess" EGBR to be associated with sources *other* than the stars in those galaxies, sources which, according to present knowledge about the era during which galaxies formed, are not capable of producing this radiation! Thus the time symmetry of a closed universe is a property which is *directly accessible to experiment* (present observations are nearly capable of performing this test), as well as extremely difficult to model convincingly on the basis of known astrophysics. In addition, the other theoretical obstacles remarked upon briefly in sections 3.B and 4 make it difficult to see how a plausible time symmetric model for the observed universe might be constructed. In particular, any such attempt must demonstrate that in a universe that is smooth whenever it is small, gravitational collapse can procede to an interesting degree of inhomogeneity when the universe is larger [36]. This is necessary in order that the universe display a thermodynamic arrow (consistently defined across spacelike slices) which naturally reverses itself as the universe begins to recollapse. Furthermore, it appears unlikely that the usual derivation of the retardation of radiation will follow through in a time symmetric universe in which radiation can connect regions displaying opposed thermodynamic arrows. Finally, in the context of the time neutral generalized quantum mechanics employed as the framework for this discussion, unless the locally observed matter-antimatter asymmetry extends globally across the present universe,[24] natural choices of CPT-related boundary conditions yield a theory with trivial dynamics if the deviations from exact homogeneity and isotropy are specified in a CPT invariant fashion (see the last paragraph of section 1.A). In sum, were the "excess" EGBR which has been the primary concern of this investigation to be observed, it would appear necessary to place the onus of explanation of the fact that the final boundary condition is otherwise practically invisible upon very specially chosen boundary conditions which encode the details of physics in our universe. This would make it difficult to understand these boundary conditions in a natural way. On the dual grounds of theory and experiment, it therefore appears unlikely that we live in a time symmetric universe. (A definitive expurgation must await more thorough investigation of at least some of the aforementioned difficulties.)

[23] Analytical elucidation of this idea is hoped to be the subject of a (far) future paper.

[24] Recall that this requires that the universe live long enough for nearly all baryons to decay, and reform into the antibaryons of the recollapsing era. This presents serious additional difficulties, *cf.* section 3.B.

Appendix: No Time Symmetric Olber's Paradox

For the malcontents in the audience, this appendix offers a flat space model explicitly illustrating the "no Olber's Paradox" argument of section 3.B. As cosmological redshifting is time symmetric, the complications due to curvature are inconsequential for present purposes. (Curvature may be included in a straightforward fashion, but that and many other embellishments are, out of courtesy, foregone.) Therefore, consider the universe of figure 1 as flat. For convenience, relocate the zero of conformal time η to be at the moment of maximum expansion. The specific energy density in radiation obeys a transfer equation

$$\frac{d\epsilon}{d\eta} = j - \Sigma\epsilon. \tag{A.1}$$

Here j represents sources (according to expanders; thus in the recontracting era j may be negative), and Σ sinks (same comment), of radiation. Time symmetry implies that

$$\epsilon(\eta) = \epsilon(-\eta), \tag{A.2}$$

$$j(\eta) = -j(-\eta), \tag{A.3}$$

and

$$\Sigma(\eta) = -\Sigma(-\eta). \tag{A.4}$$

Now, suppose it is imagined that a time symmetric universe contains only one class of localized, homogeneously and isotropically distributed sources (*i.e.* galaxies) in the expanding era, with corresponding time-reversed sinks (in the language used by expanding era observers) in the recontracting era (*i.e.* thermodynamically reversed galaxies.) For isotropically emitting sources, in the "black galaxy" approximation the absorption rate (emission rate to thermodynamically reversed observers) in the recontracting era can be thought of as being controlled by the amount of radiation from the expanding era which the recontracting era's galaxies intercept. That is, the thermodynamically reversed observers of the recontracting era would see their galaxies emitting at a rate given (at most) by

$$\begin{aligned} j(\eta) &= -\Sigma(-\eta)\epsilon(-\eta) \\ &= \Sigma(\eta)\epsilon(\eta), \end{aligned} \tag{A.5}$$

using time symmetry, and where $|\Sigma|$ is as in equation (2.19). (This is merely the expression of the fact that in the essentially geometric "black galaxy" approximation, galaxies do not care if they are intercepting radiation "from" the past or the future.) But from this it is obvious that

$$\frac{d\epsilon}{d\eta} = 0, \tag{A.6}$$

and galaxies are in radiative equilibrium with the sky, a situation reminiscent of the historically important Olber's Paradox ("Why is the night sky dark?") Thus in a transparent, time symmetric universe in which the night sky is dark, there must be an additional class of sources emitting the radiation which is correlated with the galaxies of the recontracting era.

(In reality, $j_{\rm gal} \gg \Sigma_{\rm gal}\,\epsilon$. Indeed,

$$\begin{aligned} \frac{j_{\rm gal}}{\Sigma_{\rm gal} c\epsilon} &= \frac{nL_*}{nc\sigma\epsilon} \\ &= \frac{L_*}{4\pi\sigma\nu i_\nu} \\ &\sim 10^2, \end{aligned} \tag{A.7}$$

using a characteristic galactic luminosity $L_* = 3.9\cdot 10^{43}\,{\rm erg\,s^{-1}}$ [40], $\sigma \sim 3\cdot 10^{45}\,{\rm cm^{-2}}$ (*cf.* (2.21)), (3.2), and taking $h = 1$. It should not come as a surprise that the energy density in the optical EGBR is still increasing!)

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