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## LETTERS TO NATURE

### Inflation does not explain time asymmetry

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Davies<sup>1</sup> has argued that the inflationary cosmological scenario<sup>2-5</sup> provides a natural explanation for the time asymmetry of the Universe. Here I dispute this argument by noting that the inflationary scenario implicitly invokes time asymmetry with the assumption of an absence of initial spatial correlations. No scenario based on charge-parity-time (CPT)-invariant dynamical laws can explain the time asymmetry apart from postulating or explaining these special initial conditions, as Penrose<sup>6,7</sup> has emphasized.

The time asymmetry of the Universe is expressed by the second law of thermodynamics, that entropy increases with time as order is transformed into disorder. The mystery is not that an ordered state should become disordered but that the early

Universe apparently was in a highly ordered state<sup>7</sup>. In the standard hot big-bang model, the matter (nongravitational) fields in the early Universe were not highly ordered, but the gravitational field was<sup>8</sup>. Penrose<sup>6,7</sup> pointed out that the gravitational entropy would have been enormously higher had the early Universe been composed of enormous black holes. Thus the mystery is why the early gravitational field was so smooth.

Davies<sup>1</sup> argued that this mystery is explained in the inflationary scenario<sup>2-5</sup> in which the gravitational repulsion of a false-vacuum energy density caused the early Universe to undergo exponential expansion. During this expansion, any anisotropies and inhomogeneities would asymptotically diminish exponentially (refs 9, 10, and A. A. Starobinsky, personal communication) so the gravitational field would approach the smooth de Sitter state. The argument is that this would make the gravitational field highly ordered by the time of the phase transition to a high-entropy state for the matter, so that the resulting hot Universe would then evolve as postulated in the standard big-bang model.

However, it is begging the question of time asymmetry to assume that this asymptotic decaying behaviour is what dominates the evolution of the gravitational irregularities during the false-vacuum phase. If the irregularities are viewed as perturbations of a background de Sitter space, the complete temporal

and spatial homogeneity of the latter implies that there is no *a priori* reason for supposing the perturbations get smaller with time. Nothing in the CPT-invariant dynamical equations implies this time asymmetry.

Of course, it is natural to assume that the initial perturbations spread out with time and get weaker rather than come together and get stronger, but this is a thermodynamic assumption. This unexplained time-asymmetric assumption is only 'natural' because that is how we see nature behave. We do not naturally see highly focused incoming radiation, so we postulate a time-asymmetric second law of thermodynamics to exclude it. The inflationary scenario relies on this assumption and is consistent with it, but inflation does not explain it.

The time asymmetry of the second law of thermodynamics may be elegantly expressed by the law of conditional independence<sup>11</sup> and its consequence that systems isolated in the past are uncorrelated. For a globally hyperbolic spacetime with an initial singularity (such as the big bang), this law is equivalent to the assumption that the Universe began with all spatially separated regions uncorrelated. Such an assumption makes the focusing of perturbations statistically improbable, so in an exponentially expanding phase the irregularities would tend to spread out and get weaker as the inflationary scenario assumes.

The unexplained mystery is why all spatially separated regions were apparently uncorrelated at the beginning. It would seem that they could be uncorrelated at any particular time, although interactions would generally induce correlations at all other times. Even more likely *a priori* would be for separate regions always to be correlated.

To illustrate how restrictive the second law is when expressed as an absence of initial spatial correlations, count parameters for allowed and disallowed quantum states in a schematic finite-dimensional model for the big bang. Partition an initial hypersurface (at, say, the Planck time or expansion rate) into  $n$  disjoint spatial regions, and consider the quantized matter and gravitational fields in each region as making up a quantum system with Hilbert-space dimension  $D$ . ( $D$  would ostensibly be infinite for this quantum-field-theory system, but one could imagine restricting the states to a finite  $D$ -dimensional subspace for some nonthermodynamic reason, for example to restrict the local energy.) The joint system of the  $n$  regions then has Hilbert-space dimension  $D^n$ , and its density matrix is an hermitian positive-semidefinite unit-trace  $D^n \times D^n$  matrix, which thus has  $D^{2n} - 1$  real parameters. Now these regions are uncorrelated in the quantum sense if their joint density matrix is the tensor product of the density matrices of the individual regions. The individual regions have density matrices with  $D^2 - 1$  parameters each, so an uncorrelated joint density matrix has  $n(D^2 - 1)$  parameters, which for  $D > 1$  and large  $n$  is enormously less than  $D^{2n} - 1$ . Thus the thermodynamic restriction to an uncorrelated initial state selects a subspace of far fewer parameters than those of the most general allowed states without this restriction. The unexplained mystery of the second law is the rationale for this restriction.

It is true that the inflationary scenario may allow the Universe to begin with a large amount of arbitrariness, as Davies<sup>1</sup> asserts, in that it may not depend crucially on the individual density matrices of the disjoint regions. This freedom corresponds to the  $n(D^2 - 1)$  parameters of the uncorrelated joint density matrix. But this freedom is minuscule compared with the freedom of a completely arbitrary joint density matrix.

An objection to this parameter-counting argument for the specialness of the second law is that our observations certainly do not prove that the Universe began spatially uncorrelated. Our finite observations have merely ruled out the finite number of conceivable correlations that would have produced observed antithermodynamic effects, such as focused incoming (advanced) radiation. A large class of initial correlations would doubtless have produced no such noticeable effects. Indeed, we do not even have direct evidence that the second law applies at all far away from either our past light cone or the world line of our Galaxy, so one could argue that it is rash to postulate a

universal second law for the entire Universe. If one refuses to assume a very special initial state for the Universe, one is led to the hypothesis that the order we see is a gigantic fluctuation. But then there is no reason to predict that future observations will continue to reveal more order. The fact that we remember being successful in past predictions that the order will persist has led most people to postulate that the second law in some form is universal, even though our observations can never prove that. Without knowing precisely what the second law means, it is an even bolder step to formulate it as the absence of initial spatial correlations, but that at least is one fairly definite formulation that may be defended on the grounds of simplicity. (Of course, this formulation cannot be made very precise without a theory of quantum gravity to describe the state on the initial hypersurface or whatever it is that replaces this spacetime description.)

But even if the second law should be formulated in a weaker form than the absence of initial spatial correlations, it is clearly a strong selection principle on the state of the Universe. There is no mechanism known as yet that would allow the Universe to begin in an arbitrary state<sup>1</sup> and then evolve to its present highly-ordered state.

If the inflationary scenario must invoke without explanation some thermodynamic assumption such as an initial absence of spatial correlations, one may ask whether certain other mysteries explained by the inflation would be consequences of this assumption even without inflation. It appears that the homogeneity and isotropy of the Universe may be examples of such consequences.<sup>12</sup> Because the gravitational field is coupled to matter through its stress-energy tensor, inhomogeneities in the matter must be accompanied by inhomogeneities and anisotropies in the gravitational field and generally by a non-vanishing Weyl tensor. If these nontrivial gravitational fields were spatially extended at the beginning, this would seem to require spatial correlations that the thermodynamic assumption would exclude. (Note that in this view a Friedmann cosmology has a trivial gravitational field that does not show any spatial correlations.) In other words, Penrose's suggestion<sup>6,7</sup> of an initially vanishing Weyl tensor might be a consequence of the second law of thermodynamics as formulated above. Then the observed high degree of homogeneity and isotropy of the Universe would be 'explained' by the unexplained second law even without inflation.

(This is not to say that the inflationary scenario explains nothing, for it is apparently the best solution of the cosmological monopole problem<sup>12-14</sup>. Note that this problem arose in the standard big-bang model precisely because it was assumed that the Higgs field was spatially uncorrelated initially.)

It should be clear that any special characteristic of the state of the Universe, such as its time asymmetry, cannot be explained by CPT-invariant dynamical laws alone. Without some restriction on the state, one could imagine any arbitrary conditions today (large inhomogeneities, anisotropies, and so on) and then simply evolve these backward in time by the dynamical laws to get the corresponding initial conditions needed to produce them. It seems likely that most of these past histories would not include an inflationary phase, just as in the opposite direction of time a recontracting Universe is unlikely to undergo deflation<sup>1</sup>. Thus one could say that the existence of an inflationary phase in the past puts strong limits on the present conditions of the Universe, but a demonstration of this fact would not be an explanation for these conditions, since it would leave unexplained why inflation occurred at all, much less why the inflationary phase followed the second law of thermodynamics.

Recently there have been some attempts to derive a preferred state for the Universe by a suitably restricted Euclidean path integral<sup>15,16</sup> or by quantum tunnelling from 'nothing'<sup>17,18</sup>. At present only some crude schematic characteristics of such a state can be deduced from necessarily highly approximate calculations, so it is not yet known whether these methods can explain the observed characteristics of the Universe and in particular its thermodynamic behaviour. However, it does seem clear that

only by some bold new method such as this that goes beyond mere dynamical laws can we have any hope of explaining the time asymmetry of the Universe.

It is possible that if some such method can give a preferred state for the Universe, the inflationary scenario may then have a role rather like what Davies envisages. However, there seem to be three essential elements that remain to be demonstrated for this to work: (1) The quantum analysis should somehow make it more likely for the Universe to start out small (such as, in Planck volumes at the Planck time or thereabouts), despite the enormous number of larger configurations that appear to be available. (2) It should be shown that a small Universe necessarily has low entropy. (A conjecture would be that on any spatial hypersurface in which the orthonormal spacetime curvature components are smaller than the Planck values, the entropy is less than some simple function of the number of field species present times the volume in Planck units: this inequality may be approximately saturated for the Friedmann–Robertson–Walker cosmologies at the Planck density.) (3) The inflationary phase should expand the volume of the Universe to a large

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value and then end in a phase transition which somehow manages to increase the matter entropy enormously without increasing the gravitational entropy by a comparable amount. So far none of these three elements have been clearly demonstrated, but if analyses can be developed to show them, then we might have an explanation for the second law of thermodynamics.

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## Constraints on $\gamma$ -ray bursters from soft X-ray transients

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Perhaps the most enigmatic and elusive of the short time scale astrophysical phenomena observed so far are the  $\gamma$ -ray bursts discovered in the Vela satellite data in 1973<sup>1</sup>. After a decade of observational and theoretical work, there is still no agreement on a model for the radiation detected or for the type of astronomical system responsible. We have conducted a search of the Columbia Astrophysics Laboratory's Einstein imaging proportional counter (IPC) database for possible X-ray counterparts to these transient events. The limiting sensitivity was  $\sim 10^{-10}$  erg cm<sup>-2</sup> with a total exposure of  $\sim 3 \times 10^6$  s divided amongst  $\sim 10^3$   $1^\circ \times 1^\circ$  fields. Four events with a pointlike spatial distribution were detected but their extremely soft spectra ( $kT \leq 0.1$  keV) makes them unlikely candidates for  $\gamma$ -ray burst counterparts. We use our results here to place limits on the X-ray and  $\gamma$ -ray luminosity ratio and log (number)  $N$ –log (flux)  $S$  relation for  $\gamma$ -ray bursts, and comment on the constraints placed on models for their origin.

$\gamma$ -Ray bursts have been classified into three main categories<sup>2</sup>: those for which the 5 March 1979 transient is the prototype<sup>3</sup>, those like the 20-min transient observed by Jacobson<sup>4</sup>, and 'classical'  $\gamma$ -ray bursts. The latter, encompassing most of the several hundred events observed to date, are characterized by a very short risetime ( $< 1$  s), a FWHM from 20 ms to 2 s and a total duration of 5–70 s (refs 2, 5).

The decade-long search for a satisfactory model of the burst phenomenon has been severely hampered by the lack of positive identification of the burst sources in other spectral bands despite extensive searches<sup>6–9</sup>. Only recently has evidence for counterparts in the optical<sup>10</sup> and X-ray regimes<sup>11,12</sup> been proposed. Mitrofanov<sup>13</sup>, using the observed  $\gamma$ -ray burst rate from the Konus satellite, has predicted that several dozen X-ray counter-

parts should be detectable in the Einstein Observatory database. In addition, several theoretical models for the bursts predict associated events in the X-ray regime with energies comparable with those in the  $\gamma$ -ray band<sup>14,15</sup>.

Our search for short time scale transients covered the data accumulated as part of the Columbia Astrophysics Laboratory's Einstein programme of IPC observations. The instrument<sup>16</sup> has an energy range of 0.1–4.0 keV, an effective area of  $\sim 100$  cm<sup>2</sup>, and a  $1^\circ \times 1^\circ$  field of view with a spatial resolution of 1 arc min. Approximately  $3 \times 10^6$  s of IPC data were available; the distribution of sky coverage as a function of galactic latitude is summarized in Table 1. The data were conveniently formatted in  $\sim 8 \times 8$  arc min blocks with 10  $\mu$ s time resolution and a mean background counting rate of 0.05 counts s<sup>-1</sup> per block. Thus, a 10-s integration most frequently yields values of 0 or 1 counts per block. Assuming Poisson statistics we can calculate a threshold number of counts,  $n$ , dependent only on the mean counting rate in each individual field, such that the probability of seeing  $\geq n$  counts is, say, once every  $10^6$  trials. For example, for a mean of 0.5 count per trial, corresponding to a 10-s integration,  $n = 6$ . Thus, for a typical observation of length  $\sim 2,000$  s, we expect one false alarm for every  $\sim 100$   $1^\circ \times 1^\circ$  fields. A comparison of a Poisson distribution with the observed distribution of counts per block for a 20,000-s exposure is shown in Fig. 1; the close agreement of the two distributions in the low-probability tail confirms the applicability of our threshold setting technique.

The 10-s integration period is optimum for several operational as well as astrophysical considerations. The reality of an event containing fewer than 7 or 8 photons is, for a detector with finite background, statistics-limited, so a shorter integration time is of no advantage. On the other hand, an event of the same flux lasting more than  $\sim 50$  s (40 total counts) would emerge above the background as an identifiable source in the integrated image and, thus, would have been catalogued by the automatic source detection algorithm and tested for variability. We checked  $\sim 500$  such new sources discovered in our database and, while a few examples of clear variability emerged, none of the sources either appeared or disappeared on time scales shorter than the observation ( $> 10^3$  s). Finally,  $\sim 10$  s is the