C. R. Physique 16 (2015) 928–947

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Cosmic inflation / Inflation cosmique

Causal structures in inflation

Structures causales de l'inflation

George F.R. Ellis [a], Jean-Philippe Uzan [b,c,*]

[a] *Mathematics and Applied Mathematics Department, University of Cape Town, Rondebosch, Cape Town 7701, South Africa*
[b] *Institut d'astrophysique de Paris, UMR 7095 du CNRS, Université Pierre-et-Marie-Curie, 98 bis, boulevard Arago, 75014 Paris, France*
[c] *Sorbonne Universités, Institut Lagrange de Paris, 98 bis, boulevard Arago, 75014 Paris, France*

ARTICLE INFO

Article history:
Available online 2 September 2015

Keywords:
Cosmology
Inflation
Causal structures

Mots-clés :
Cosmologie
Inflation
Structures causales

ABSTRACT

This article reviews the properties and limitations associated with the existence of particle, visual, and event horizons in cosmology in general and in inflationary universes in particular, carefully distinguishing them from 'Hubble horizons'. It explores to what extent one might be able to probe conditions beyond the visual horizon (which is close in size to the present Hubble radius), thereby showing that visual horizons place major limits on what are observationally testable aspects of a multiverse, if such exists. Indeed these limits largely prevent us from observationally proving a multiverse either does or does not exist. We emphasize that event horizons play no role at all in observational cosmology, even in the multiverse context, despite some claims to the contrary in the literature.

© 2015 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

RÉSUMÉ

Cet article définit, puis passe en revue les propriétés et les limites associées à l'existence d'horizons (des particules, des événements et visuels) en cosmologie en général et pendant l'inflation en particulier, en insistant sur leurs différences avec les « horizons de Hubble ». Il discute la possibilité de tester les conditions physiques de l'univers au-delà de notre horizon visuel (qui, en taille, est proche du rayon de Hubble) et démontre que l'existence d'horizons visuels impose des limites strictes sur ce qui est potentiellement testable dans les scénarios de type multivers, s'ils existent. Ces limites nous interdisent de prouver observationnellement l'existence ou la non-existence de ces multivers. Il est aussi démontré que les horizons des événements ne jouent aucun rôle en cosmologie observationnelle, même dans le contexte des modèles de multivers.

© 2015 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

1. Introduction

The causal structure of spacetimes plays a major role in the understanding of the physics of black holes and in cosmology. In particular these spacetime possess horizons. A horizon is a frontier that bounds causality, or separates observable events

---

[*] Correspondence to: Institut d'astrophysique de Paris, 98 bis, bd Arago, 75014 Paris, France.
E-mail addresses: george.ellis@uct.ac.za (G.F.R. Ellis), uzan@iap.fr (J.-P. Uzan).

http://dx.doi.org/10.1016/j.crhy.2015.07.005
1631-0705/© 2015 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

from non-observable ones. In cosmology they limit the observational possibilities, and they have to be distinguished from the natural scales fixed by the cosmic expansion rate. The way they do so differs in non-inflationary and inflationary cosmology.

These hypersurfaces play different roles in their two main contexts, the physics of black holes and cosmology [1–6]. We focus here on their role in cosmology, but contrast this with the black hole case. There appears to be substantial confusion about this in some of the current literature on inflationary cosmology, where in particular event horizons are claimed to play a significant physical role; but this is not the case.

The article is organized as follows: Section 2 defines the different notions of horizons, and Section 3 focuses on the use of conformal diagrams. Section 4 discusses the case of standard cosmology, while Sections 5 and 6 consider inflationary cosmology and alternative models, including small universes and some multiverse proposals.

2. Different notions of horizons

Very different concepts of horizons have to be considered. In particular, one needs to distinguish between *local* and *non-local* (or *global*) notions of horizons, respectively defined in Section 2.2 and Section 2.3.

In order to introduce all these notions, we firstly assume that the spacetimes under consideration are globally hyperbolic so that they can be foliated by a continuous family of spacelike three-dimensional hypersurfaces, Σ_t [3]. This means that there exists a smooth function $\hat{t}$ on $\mathcal{M}$ whose gradient never vanishes and is timelike so that each hypersurface is a surface of constant $\hat{t}$,

$$\Sigma_t = \{p \in \mathcal{M},\ \hat{t}(p) = t\} \tag{1}$$

$\forall t \in I \subset \mathbb{R}$ and $g^{\mu\nu}\hat{t}_\mu\hat{t}_\nu < 0$ where I is a maximal subset of $\mathbb{R}$ so that Σ_t covers all $\mathcal{M}$. Such spacetimes represent most spacetimes of astrophysical and cosmological interest. They imply existence of a global direction of time. The expansion of the universe, and associated physically meaningful horizons, occur relative to the future direction of time.

Secondly, in the cosmological case, we assume existence everywhere of a family of fundamental observers with 4-velocity $u_\mu : u^\mu u_\mu = -1$, defining a preferred cosmological restframe at each point [7,8]. This implies that the worldlines of fundamental observers never intersect.

2.1. Past light cone

Given a spacetime $\mathcal{M}$ with metric $g_{\mu\nu}$, one can define for any event p the past lightcone $C^-(p)$ as the set of events q such that there exists a future directed null geodesic joining q to p. It characterizes the set of events that can be observed by an observer at event p by electromagnetic radiation, irrespective of its wavelength. Technically, for any event q on $C^-(p)$, there exists a null geodesic $x^\mu(\lambda)$ parameterized by the affine parameter $\lambda \leq 0$ (chosen negative so that increasing λ corresponds to the future direction of time), such that $x^\mu(0) = p$ and there is a value λ_1 such that $x^\mu(\lambda_1) = q$. Its tangent vector $k^\mu \equiv dx^\mu/d\lambda$ satisfies the null geodesic equation

$$k^\mu k_\mu = 0, \qquad k^\mu \nabla_\mu k^\nu = 0 \tag{2}$$

The past lightcone is a 3-dimensional null surface that can be parameterized by 2 angles (θ, ϕ) representing the direction of observation in the sky and a redshift z that characterizes the distance "down" the lightcone, and is defined as

$$1 + z \equiv \frac{(-k^\mu u_\mu)_{\text{source}}}{(-k^\mu u_\mu)_{\text{obs}}} \tag{3}$$

where u^μ is the tangent vector to the observer and source worldlines. These quantities are defined with respect to the fundamental observers. By construction, $C^-(p)$ depends on the event p so that two different observers have different lightcones, and any specific observer's lightcone changes over time. In cosmology, this latter effect is at the origin of the time drift of observed redshift [9].

Let us recall an important property. Consider two spacetimes whose metrics $g_{\mu\nu}$ and $\tilde{g}_{\mu\nu}$ are conformal, i.e. $g_{\mu\nu} = \Omega^2 \tilde{g}_{\mu\nu}$. Any null geodesic of $g_{\mu\nu}$ with affine parameter λ is a null geodesic of $\tilde{g}_{\mu\nu}$ with affine parameter $\tilde{\lambda}$ where $\mathrm{d}\lambda = \Omega^2\,\mathrm{d}\tilde{\lambda}$, so that $\tilde{k}^\mu = \Omega^2 k^\mu$; see, e.g., Ref. [10].

2.2. Non-local horizons

We can define several types of non-local horizons, namely particle horizons [2], visual horizons [11,12] and event horizons [2]. They are non-local in the sense that they depend on the large-scale geodesic structure of the spacetime. They are defined relative to the future direction of time.

Download English Version:

https://daneshyari.com/en/article/1858541

Download Persian Version:

https://daneshyari.com/article/1858541

Daneshyari.com