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LETTER

Entropy of viscous Universe models

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Abstract The cosmological event horizon entropy and the apparent horizon entropy of the ΛCDM and the Bianchi type I Universe model with viscosity has been calculated numerically, and analytically in the large time limit. It is shown that for these Universe models the cosmological event horizon entropy increases with time and for large times it approaches a finite maximum value. The effect of viscosity upon the entropy is also studied and we have found that its role is to decrease the entropy. The bigger the viscosity coefficient is the less the entropy will be. Furthermore, the radiation entropy for the ΛCDM Universe model with and without viscosity is investigated, and together with the cosmological event horizon entropy are used to examine the validity of the generalized second law of thermodynamics, which states that the total rate of change of entropy of the Universe is never negative, in this Universe model.

Keywords Entropy · Viscous Universe models · Cosmological event horizon entropy · Radiation entropy · Cosmic radial coordinate · Viscosity · Generalized second law of thermodynamics

1 Introduction

The arrow of time is deeply connected to the rate of change of entropy in the universe. According to the second law of thermodynamics the entropy of the Universe is an increasing function of time. A homogenous Universe is in a state of thermal equilibrium with equal temperature everywhere on a present scale above some hundred million light years. Such a Universe is in a state of maximal thermal entropy.

The expansion of such a universe filled by different types of non-interacting perfect fluids is adiabatic. Hence it has always been in a state of large scale maximal entropy. Hence such simple universe models do not provide information about the time evolution of thermal entropy in the Universe. In this connection it is the deviation from homogeneity, or the deviation from perfection of cosmic fluids, or interactions between different fluids in the Universe that are interesting.

Observations of the temperature fluctuations of the cosmic microwave background (Planck collaboration 2013) show that the deviations from homogeneity in the cosmic fluid were extremely small around 400 000 years after the Big Bang. Hence the thermal entropy of the cosmic fluid was nearly maximal.

So there is a problem: How can the cosmic entropy be an increasing function of time when it was so close to a maximum at the beginning of the evolution of the Universe? There are several answers to this question. A common element in the answers is that there must exist other types of entropy than thermal entropy.

Due to the weakness of gravity it can safely be neglected for the description of thermodynamics of systems on a human scale at the present time. Then evolution towards temperature equality means increasing thermal entropy. It is tempting, then, to think that clumping of matter into stars which produces great temperature differences, leads to lower thermal entropy.

This might motivate to define a gravitational entropy that increases with increasing clumping of matter. One sugges-

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