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THE GRAVITATIONAL INFLUENCE OF QUASAR CLUSTERS ON THE COSMIC BLACK BODY RADIATION

by

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Summary

The cosmic black body radiation is observed to be highly isotropic, but if quasar clusters exist their gravitational effect should induce small (~ 0.1 per cent) anisotropies in the radiation. There is some preliminary evidence in favour of this idea and so it seems worth discussing in detail. We begin by examining the possibility that quasars are clustered, and then we calculate the gravitational effect the clusters would have on the effective temperature of the black body radiation. The effect depends significantly on whether the universe has a low density or a high density, and would be observable in future experiments.

It now seems almost certain that the excess microwave radiation discovered by Penzias and Wilson[1] in 1965 is black body radiation left over from the hot big bang origin of the universe.[2] The radiation is highly isotropic,[3] but it may contain small anisotropies arising from the gravitational effects of large clusters of quasars[4]. This proposal is quite speculative at the moment, but we believe that the possibility is sufficiently likely and interesting to be worth discussing in some detail.

Quasar Clusters

About a year ago we[5] suggested that quasars may be clustered in much the same way as galaxies are. This seemed to us the natural inference from the discovery of Strittmatter, Faulkner, and Walmsley[6] that quasars with large red shifts do not appear to be distributed randomly in the sky. The evidence on this point is scanty at the moment, and plagued with ill-understood selection effects, but is certainly worth taking seriously.

What might we expect for the angular and linear size of an observable quasar cluster? According to Sandage and Luyten[7] there are about 0.4 quasars per square degree down to a blue magnitude of 18. Thus the minimum detectable angular scale of a cluster would be a few degrees. In fact only about 200 quasars have so far been discovered, and these would be too sparsely distributed over the sky to reveal any clustering on an angular scale less than 10 or 20 degrees. Now a freely expanding cluster with a red shift of, say, 1.5 and subtending an angle of about 20 degrees would by now have linear dimensions of ~750 megaparsecs in an Einstein-de Sitter universe.

This is an appreciable fraction of the present 'radius' of the universe (~3,000 megaparsecs) and so the question arises: is it meaningful to consider that irregularities may exist on such a large scale? This is a difficult question because we do not yet understand the origin of the known smaller-scale irregularities in the universe. It may, however, be helpful to consider what is known or reasonably conjectured about these irregularities. This information is summarised, in very round figures, in the following table, where we have assumed that the present mean density ρ_0 in the universe $\sim 10^{-30}$ gm.cm^{-3}.

Observed Clustering in the Universe

Scale	Object	Density Contrast $\left(\frac{\delta\rho_0}{\rho_0}\right)$
30 kiloparsecs	Galaxy	10^6
1 megaparsec	Galaxy Cluster	10^3
30 megaparsecs	Supercluster	10
1000 megaparsecs	?	?

It does not seem out of the question that on a scale of ~ 1,000 megaparsecs there should be quasar clusters in which $(\delta\rho_0/\rho_0)$ is of the order of unity. If the rate of formation of quasars depends on some power of the ambient density, (as seems to be the case with stars where the power involved is ~ 2 (ref.8)), or if the lifetime or brightness of quasars is enhanced by the higher density, the concentration of quasars would help to delineate the overall density distribution, and quasar clustering might be detectable.

Further insight into the possibility that there may be large-scale irregularities in the universe can be gained from a consideration of the behaviour of perturbations of various scales during the expansion of a hot big bang universe. This problem involves a fascinating interplay of general relativity and cosmical gas dynamics which lack of space forbids us to discuss. Suffice it to say that the large irregularities of interest to us here exceed the horizon size of the universe until relatively recently, when radiation and matter are uncoupled, and no important damping mechanisms can come into play. Everything thus depends on the initial amplitude of these irregularities, and there is no known reason why this should be a negligible fraction of the amplitude of the irregularities which develop into, say, superclusters of galaxies.

The Gravitational Effect of Large-Scale Irregularities on the Cosmic Black Body Radiation

In a homogeneous expanding universe, the black body radiation cools off according to the law

$$T \propto 1/R(t) \qquad (1)$$

where T is the radiation temperature and R is the scale factor of the universe. Equivalently we may write

$$T \propto \frac{1}{(1+z)} \qquad (2)$$

where z is the red shift relating the observer to an arbitrary point on the radiation's path. Now if there is a density irregularity on the line of sight the red shift will be altered by gravitational effects, and so the temperature of the black body radiation coming from that direction will be altered too: we can no longer apply (1), even though (2) still holds. This was first pointed out by Sachs and Wolfe[9] independently of the question of quasar clustering. Their method of calculation is not readily adapted to our problem, and so we shall present a different type of analysis here.

Let us first consider the unperturbed relation

$$(1+z) = \frac{R(t_B)}{R(t_A)} \qquad (3)$$

for the red shift between two observers A and B in a uniform expanding universe. Radiation reaching B at t_B is assumed to have passed A at t_A. We may attribute this red shift to the gravitational field, and the motion, of a comoving spherical region with diameter AB. It can then be regarded as arising from three effects:

(i) a <u>blue</u> shift resulting from the fact that the delay in the light travel time due to the gravitational field between A and B is itself decreasing with time,

(ii) a straightforward Doppler red shift,

(iii) a gravitational red shift.

These effects combine to give the red shift (3), but it is useful to enumerate them separately in order to be able to deal with the situation when there is an irregularity along the line of sight.

The type of irregularity which we shall consider is one in which the matter within a comoving sphere is replaced by a uniform sphere of the same mass but lower kinetic energy. The remainder of the universe is unaffected by the irregularity, which very much simplifies the discussion. The change in effect (i) due to the irregularity will then be $2M\left(\frac{v'}{R'} - \frac{v}{R}\right)$, where M is the mass, v the velocity and R the radius of the sphere ($M/R \ll 1$) and the " ' " refers to the perturbed values. The deeper potential well in the cluster results in an extra time delay. In consequence the radiation reaching B at t_B must have left A before t_A, at which time it was correspondingly hotter. There is thus an additional effect (iv) which produces a fractional temperature increase $\frac{2Mv}{R} \log\left(R/R'\right)$. The extra time delay causes changes in (ii) and (iii) which are, however, $\sim M/R$ times smaller. Our final result is thus

$$\frac{\Delta T}{T} \simeq 2M\left\{\frac{v'}{R'} - \frac{v}{R}\left(1 - \log\frac{R}{R'}\right)\right\} \qquad (4)$$

It is easy to show that in a very low density universe ΔT is positive, whereas in an Einstein-de Sitter universe it is negative. The magnitude of ΔT is illustrated by the example of a cluster with a present size of 750 megaparsecs, a contrast density of 3 and a red shift 1.5 in an Einstein-de Sitter universe. In this case $\frac{|\Delta T|}{T} \sim 0.3$ per cent. This result refers to a line of sight passing through the centre of the cluster. One may also calculate the temperature profile obtained by scanning across the cluster, and this too is characteristically different in a low density and a high density universe.

This whole discussion would be rather academic if there were no hope of detecting the effects we have described. Fortunately the prospects are quite good. Indeed after our original suggestion that there might be observable variations in the black body background in the direction of the suspected quasar clusters, Wilkinson and Partridge[10] reported a possible variation ~ 0.5 per cent in the direction of the cluster near the south galactic pole, and on the same angular scale. The observations are only marginally significant, and much more work needs to be done.

Conclusions

We hope that in the next few years the temperature variations in the black body background radiation will be mapped out over the whole sky to a precision of better than 0.1 per cent. This map can then be compared with the angular distribution of quasars of known red shift to see whether there is any significant correlation. If there is, then we will learn much about quasar clusters and the spectrum of irregularities in the universe at the long wavelength end of the scale. In this way the influence of gravity on radiation would represent, not merely a test of general relativity, but a tool for exploring new aspects of the structure of the universe.

References

1. A.A. Penzias and R. Wilson, Ap. J. 142, 419 (1965)
2. R.H. Dicke, P.J.E. Peebles, P.S. Roll, D.T. Wilkinson, Ap. J. 142, 414 (1965)
3. R.B. Partridge and D.T. Wilkinson, Phys. Rev. Letters 18, 557 (1967); E.K. Conklin and R.N. Bracewell, Nature 216, 777 (1967)
4. M.J. Rees and D.W. Sciama, Nature 217, 511 (1968)
5. M.J. Rees and D.W. Sciama, Nature 213, 374 (1967)
6. P.A. Strittmatter, J. Faulkner, M. Walmsley, Nature 212, 1661 (1966)
7. A. Sandage and W.J. Luyten, Ap. J. 148, 767 (1967)
8. M. Schmidt, Ap. J. 129, 243 (1959)
9. R.K. Sachs and A.M. Wolfe, Ap. J. 147, 73 (1967)
10. D.T. Wilkinson and R.B. Partridge, Nature 215, 719 (1967)

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