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LUMINOSITY ENHANCEMENT OF DISTANT RADIO GALAXIES AND VARYING *G* HOYLE–NARLIKAR COSMOLOGY

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Abstract. We investigate the time evolution of galactic luminosity in the framework of the Hoyle–Narlikar (HN) cosmology with a variable gravitational constant G. The luminosity evolution with redshift is studied for both black-body and power-law sources. The G varying HN cosmological models are seen to predict systematically higher luminosities for galaxies at earlier epochs. For thermal black-body sources the increase in infrared K-band luminosity is estimated to be about 1.5 mag for a redshift of $z \approx 1$. Also the higher temperatures at earlier epochs implied by these models would make the distant galaxies appear bluer. For sources with power-law spectra the magnitude changes are even larger. There is some measure of observational support for the above theoretical predictions.

1. Introduction

The recent advances made in observational astronomy have added to the importance of the study of luminosity evolution of extragalactic objects. While quasars with redshifts beyond $z \approx 4$ have been discovered, observations for galaxies with $z \approx 2$ are becoming available, making it possible to investigate the changes in the properties of these objects over a period extending to look-back times which are significant fractions of the present age of the Universe.

In this paper we initiate an investigation of luminosity evolution of extragalactic objects within the framework of the cosmological theory of Hoyle and Narlikar (1964, 1974, referred to hereafter as HN). Previously, Canuto and Narlikar (1980, referred to hereafter as CN) had subjected the HN theory to various tests of observational cosmology and came to the conclusion that the HN theory fared equally well as the 'standard' cosmology in all the observational tests. This work is, in a way, an extension of the work done by CN and we shall make frequent use of the techniques developed by CN.

We shall start with a very brief outline of the HN theory, limiting ourselves to the equations and formulae required in the present context. We shall then derive the required equations, etc., which will be used in the next section.

2. HN Cosmology: a Brief Outline

The HN theory of gravitation is based on the Machian view that the inertia of a particle is due to the rest of the particles of the Universe. This theory presents many novel features from the observational point of view. Here we shall be concerned with the

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1988Ap&SS.143..249D

cosmological implications of the prediction of a variable gravitational constant G. As mentioned above we shall merely list the equations and formulae needed here. For details see CN (1980, *op. cit.*).

We use the so-called 'Atomic Gauge' in which the cosmological line element is

$$ds^2 = c^2\,dt^2 - 2H_0 t\,[dr^2 + r^2(d\theta^2 + \sin^2\theta\,d\phi^2)]\,. \tag{1}$$

Hence, the expansion factor $S(t) = \sqrt{2H_0 t}$ and the Hubble constant

$$H(t) = \dot{S}/S = \frac{1}{2t}\,. \tag{2}$$

We also note that the HN cosmology is uniquely specified by the curvature parameter $k = 0$ and the deceleration parameter $q = 1$ *at all epochs*.

In this gauge the particle masses are constant but the gravitational 'constant' G is epoch-dependent and is given by

$$G(t) = \frac{G_0}{2H_0 t}\,, \tag{3}$$

where the suffix 0 denotes the present epoch $t = t_0$.

A photon emitted at epoch t and received at epoch t_0 suffers a redshift z given by

$$(1 + z) = \frac{S(t_0)}{S(t)} \equiv \frac{S_0}{S} = \sqrt{\frac{t_0}{t}}\,. \tag{4}$$

From Equations (3) and (4) we obtain

$$G(t) = G_0(1 + z)^2\,, \tag{5}$$

since $H_0 = (2t_0)^{-1}$.

3. Luminosity Evolution in the HN Cosmology

3.1. Redshift-Magnitude Relations

Consider a source (galaxy) at an epoch t and at a coordinate distance r in the Robertson–Walker space-time with luminosity L and normalized intensity function $J(\nu)$. A photon emitted with a frequency ν will be observed by us at $r = 0$, $t = t_0$ with a frequency ν_0 given by

$$\nu_0 = \frac{\nu}{(1 + z)}\,. \tag{6}$$

In standard cosmology the observed flux density at the frequency ν_0 is given by

$$f(\nu_0) = \frac{L[J\{\nu_0(1 + z)\}]}{4\pi D^2}\,(1 + z) \tag{7}$$

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1988Ap&SS.143..249D

(Narlikar, 1983); where

$$\int_0^\infty J(\nu)\,\mathrm{d}\nu = 1\,,$$

and the luminosity distance

$$D = rS(t_0)\,(1 + z)\,. \tag{8}$$

In the HN cosmology both luminosity L and the gravitational constant G are epoch dependent. By arguments similar to those leading to the derivation of Equation (3.4) of CN, it can be shown that the flux density in this case is given by

$$f(\nu_0) = \frac{L(t)\,[J\{\nu_0(1 + z)\}]}{4\pi D^2}\,(1 + z)\,\frac{G(t)}{G_0}\,. \tag{9}$$

Converting into the apparent magnitude $m(\nu_0)$ we obtain

$$m(\nu_0) = -2.5\log f(\nu_0) + \text{constant}\,,$$

or

$$m(\nu_0) = \text{constant} + 5\log D - 2.5\log[(1 + z)J\{\nu_0(1 + z)\}] - - 2.5\log[L(t)G(t)/G_0]\,.$$

Following CN, we shall write the epoch dependence of L and G in the form

$$\frac{G(t)}{G_0} = \left(\frac{t}{t_0}\right)^{-g} = (1 + z)^{2g}$$

and

$$\frac{L(t)}{L_0} = \left(\frac{t}{t_0}\right)^{-e} = (1 + z)^{2e}\,, \tag{10}$$

where the evolutionary parameter $g = 1$ (see Equation (5)) and the other evolutionary parameter e will be discussed later.

Substituting $D = rS_0(1 + z) = (c/H_0)z$ for the HN cosmology we obtain

$$m(\nu_0) = \text{constant} + 5\log z - 2.5\log[(1 + z)J\{\nu_0(1 + z)\}] - - 5(e + g)\log(1 + z)\,. \tag{11}$$

To facilitate comparison of intrinsic luminosities we write Equation (11) in terms of absolute magnitude M – i.e.,

$$m(\nu_0) - M(\nu_0) = m_{\text{bol}} - M_{\text{bol}} = 5\log(D)_{pc} - 5$$

(Weinberg, 1972); yielding

$$M(\nu_0) = C' - 2.5\log[(1 + z)J\{\nu_0(1 + z)\}] - 5(e + g)\log(1 + z)\,, \tag{12}$$

where C' is a constant.

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1988Ap&SS.143..249D

3.2. Forms of the intensity function

We now require a specific form for $J(\nu)$. This will depend on the radiation processes responsible for producing the luminosity. As thermal black-body radiation is usually assumed to account for the bulk of the luminosity in the optical and near-infrared (till 20μ) we assume $J(\nu)$ to have a black-body form. Later we shall also investigate the case when the spectrum has a power-law nature.

(a) The radiation energy density within a frequency interval $\mathrm{d}\nu$ from ν to $\nu + \mathrm{d}\nu$ for black-body radiation is given by the usual expression

$$\rho(\nu, T)\, d\nu = \frac{8\pi\nu^2}{c^3} \frac{h\nu}{[\exp(h\nu/KT) - 1]}\, \mathrm{d}\nu$$

with

$$\rho(T) \equiv \int_0^\infty \rho(\nu, T)\, \mathrm{d}\nu = aT^4 ,$$

where radiation constant $a = \frac{8}{15}\pi^5 K^4 h^{-3} c^{-3}$.

Since $J(\nu)$ is normalized, we define

$$J(\nu) \equiv J(\nu, T) = \rho(\nu, T)/aT^4 ;$$

yielding

$$J(\nu) = \frac{15}{\pi^4 \nu}\left(\frac{h\nu}{KT}\right)^4 \frac{1}{\left[\exp\left(\frac{h\nu}{KT}\right) - 1\right]} . \tag{13}$$

Substitution in Equation (12) yields

$$M(\nu_0) = C - 2.5[1 + 2(e + g)]\log(1 + z) - $$
$$- 2.5 \log\left[\frac{\nu_0^3(1 + z)^3}{T^4} \frac{1}{\left[\exp\left\{\frac{h\nu_0(1 + z)}{KT}\right\} - 1\right]}\right], \tag{14}$$

where C is a constant.

We now investigate the evolution of the galactic temperature T. The evolution of the temperature of an isolated star in the HN cosmology is given by

$$T_{\text{star}} \propto \left[\frac{G^{(1+t)}}{g} g^{(2+2t)}\right]^{q-1} , \tag{15}$$

(CN, Equation (4.16)), where $t \equiv r + s$, $q \equiv n + m + 3t, f = G^{-1}$, $r = s = 1$, $n = -3.5$,

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1988Ap&SS.143..249D

and $M = 4.5$ (for Kramers's opacity and the p–ρ cycle) and $g \equiv GM$ (not to be confused with the evolutionary parameter g occurring elsewhere). Substitution of numerical values yields

$$T_{\text{star}} \propto G^{10/7} M_{\text{star}}^{6/7} . \tag{16}$$

To calculate the total luminosity of a galaxy it is necessary to integrate the stellar luminosity function over a range of stellar masses from M_L to M_f with a given Initial Mass Function (IMF) (CN, IV(b)). But following CN we can make a simplifying assumption. Since the major contribution to the luminosity of the galaxy (especially in the near-infrared) comes from the massive giants and supergiants, that is from stars with masses near the upper cut-off M_f, we shall be justified in assuming that the average temperature of the galaxy will be proportional to the temperature of a single star of mass M_f. Hence, we have from Equation (16)

$$T_{\text{gal}} \propto G^{10/7} M_f^{6/7} . \tag{17}$$

However, for a single star in the HN cosmology the constraint

$$GM_{\text{star}} \propto \sqrt{G} \tag{18}$$

applies. Hence, we finally obtain

$$T_{\text{gal}} \propto G ;$$

or, on dropping the suffix gal,

$$T \propto (1 + z)^2 . \tag{19}$$

Incidentally, as this implies higher temperatures at earlier epochs, the galaxies should appear systematically bluer in the past, a result consistent with the observations of Lilly *et al.* (1983). Djorgovski *et al.* (1984) and obtained without needing to postulate an extra component of O stars or bursts of star formation.

With $T = T_0(1 + z)^2$, Equation (14) becomes

$$M(\nu_0) = C - 2.5 \log\left(\frac{\nu_0^3}{T_0^4}\right) + [10 - 5(e + g)] \log(1 + z) - 2.5 \log f(z) , \tag{20}$$

where

$$f(z) = \frac{1}{\exp\{h\nu_0/KT_0(1 + z)\} - 1} .$$

which is the required expression.

We note that $f(z)$ is an increasing function of z. Hence, the last term will tend to decrease $M(\nu_0)$ for a larger z.

(b) Radio sources often exhibit a power-law spectrum of the form $J(\nu) \propto \nu^{-\alpha}$ which is believed to be due to synchrotron radiation arising from an electron-energy spectrum of the form $N(p) \propto p^{-s}$ where $\alpha = \frac{1}{2}(s - 1)$. For a power-law source we have from

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1988Ap&SS.143..249D

Equation (12)

$$M(\nu_0) = C - 2.5 \log[(1 + z)\nu_0^{-\alpha}(1 + z)^{-\alpha}] - 5(e + g) \log(1 + z),$$

or

$$M(\nu_0) = C - 2.5[(1 - \alpha) + 2(e + g)] \log(1 + z) + (2.5\alpha) \log \nu_0 . \tag{21}$$

4. Discussion

We are now in a position to estimate the luminosity evolution of galaxies as predicted by the HN theory. Consider the thermal sources first.

We compare the absolute magnitude of two identical galaxies, one with zero redshift, that is at the present epoch t_0, and the other with a redshift z that is at an epoch $t = t_0/(1 + z)^2$, observed at frequency ν_0. From Equation (20) we obtain

$$M(\nu_0)|_{z=0} - M(\nu_0)|_z = [5(e + g) - 10] \log(1 + z) - 2.5 \log\left[\frac{f(z = 0)}{f(z)}\right]. \tag{22}$$

In Equation (22) we have $g = 1$. The luminosity evolutionary parameter e has been discussed extensively by CN and is found to depend critically on various factors such as the opacities of the constituent stars, the value of the Salpeter Initial Mass Function (IMF), etc. CN find that $e \lesssim \frac{3}{2}$ for galaxies whereas $e \lesssim \frac{3}{5}$ for QSOs and radio galaxies. Here we choose $e \approx 1$ as a representative value; and if so, Equation (22) then becomes

$$\Delta M(\nu_0)|_z = M(\nu_0)|_{z=0} - M(\nu_0)|_z = -2.5 \log\left\{\frac{f(z = 0)}{f(z)}\right\}. \tag{23}$$

For the power-law sources Equation (21) yields

$$\Delta M|_z = 2.5[(1 - \alpha) + 2(e + g)] \log(1 + z). \tag{24}$$

As an illustrative numerical example we calculate the changes in magnitudes for a redshift of unity. For the black-body case let us consider emission in the infrared K band. For this $\lambda_0 = 2.2\mu$ and we choose $T_0 = 3 \times 10^3$ K which seems reasonable. From Equation (20) we then get

$$f(z) = \frac{1}{\exp\left\{\frac{2.18}{1 + z}\right\} - 1} . \tag{25}$$

For $z \approx 1$ we obtain from Equation (23) $\Delta M|_{z \approx 1} \approx 1.5$ which means galaxies at $z \approx 1$ are intrinsically brighter by $\sim 1.5^m$ than the nearby ones.

For the power-law sources with the usual value $\alpha \approx 0.7$ we obtain with $g = 1$, $e \approx 1$, $\Delta M|_z \approx 10.75 \log(1 + z)$, yielding a somewhat higher value $\Delta M|_{z \approx 1} \approx 3.2$.

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1988Ap&SS.143..249D

It is interesting to compare these theoretical predictions with the recent observational work. For example, extensive observations recently made by Lilly and Longair (1984) on radio galaxies associated with 3CR sources over a redshift range of $0 < z < 1.6$ suggest systematic brightening of distant galaxies. From an analysis of the infrared Hubble (K, z) relation of these sources, Lilly and Longair conclude that the infrared luminosity evolution amounts to a change of slightly more than a magnitude in the absolute magnitude of a galaxy out to $z \gtrsim 1$ for a Friedmann cosmology with $q_0 \lesssim 0.5$. They attribute this change to the changing number of red giants in the population due to evolution of the Main-Sequence turn-off mass in a passively evolving galaxy. A re-analysis of Lilly and Longair's data by Wampler (1987) has led to similar conclusions. Similarly, detailed investigations by Djorgovski *et al.* (1984, and references given therein) of the magnitudes and colours for a sample of distant 3CR radio galaxies with redshifts up to $z \approx 1.82$ show very dramatic evidence for luminosity and colour evolution of these objects. From a study of the V-band Hubble diagram of these objects they find a luminosity excess of about 5^m–6^m for $z \approx 1.8$. While Djorgovski *et al.* interpret their data by using the evolutionary models of Bruzual (1983), Hammer *et al.* (1986) have attempted an interpretation on the basis of amplification due to gravitational lensing which acts concurrently and probably complementarily with the evolution.

The present work shows that the luminosity enhancement of distant galaxies arises as a natural consequence of variation of G in the HN cosmology, and the predicted changes are of the same order as those obtained from observational data in the framework of Friedmann cosmologies.

5. Concluding Remarks

The Hoyle–Narlikar G varying cosmological models are seen to predict higher luminosities for galaxies at earlier epochs. For thermal black-body radiation the increase in infrared K band luminosity is about 1.5 mag for a redshift of $z \approx 1$ whereas for sources with power-law spectra the luminosity changes predicted by HN models are somewhat larger. Also the higher temperatures at earlier epochs implied by these theoretical models would make the distant galaxies systematically bluer. There is some measure of observational support for these theoretical predictions from the works of Lilly and Longair (1984), Lilly *et al.* (1983), Wampler (1987), and Djorgovski *et al.* (1984).

One advantage of HN cosmology is that it is uniquely specified by curvature parameter $k = 0$ and deceleration parameter $q = 1$ and, therefore, makes clear, parameter free predictions, unlike the models in 'standard' cosmology. Here we have shown that two observed features in distant galaxies follow as definitive predictions of the HN theory without the need to invoke *ad hoc* evolutionary changes or involve an extra component of O stars. Other *ad hoc* explanations like bursts of star formation or aplification by gravitational lens which are used in conventional Friedmann models also are not needed in the present model. We feel that the encouraging results obtained in this preliminary work will justify a more rigorous investigation of HN cosmological models to study the luminosity evolution of distant objects.

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1988Ap&SS.143..249D

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