Adv. Space Res. Vol.3, No.10-12, pp.473-476, 1984
Printed in Great Britain.

0273-1177/84 \$0.00 + .50

THE INFRA-RED BACKGROUND GENERATED BY PREGALACTIC STARS AND THEIR REMNANTS

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ABSTRACT

We examine whether the IR background reported by Matsumoto (1983) could have been generated by stars or black holes in the pregalactic era, $z=10\sim100$.

KEYWORDS

Infra-red astronomy; background radiation; cosmology; population III stars; accretion by black holes.

INTRODUCTION

Matsumoto, Akiba and Murakami (1983) have claimed to detect an IR background in the waveband 1.4μ-5μ. They argue that the intensity is too high to be explained by atmospheric, planetary or galactic sources and that it may have been generated by pregalactic (population III) stars Such stars have been invoked for a variety of reasons (Carr, Bond and Arnett, 1983; Doroshkevich, Zeldovich and Novikov, 1967; Sato, Matsuda and Takeda, 1971), in particular, to produce pregalactic heating, element enrichment, galaxy formation and dark matter. An IR background has long been anticipated as a possible signature of their existence (Peebles and Partridge, 1967; Thortsensen and Partridge, 1975). If the observed flux really is a cosmic background, its energy density is comparable with that of the microwave background and $\Omega_R\sim10^{-4}$ in units of the critical density ($\rho_{cr}=5\cdot10^{-30}h^2 g\ cm^{-3}$ with $H_0=50h$ km $s^{-1}Mpc^{-1}$). In this note, we examine possible models which explain this flux by invoking pregalactic stars or black holes (Carr, McDowell and Sato, 1983; Hayakawa, 1982).

THE BACKGROUND GENERATED BY STARS

We first estimate the background flux from stars in the mass range 200-$10^5M_\odot$. More massive stars are excluded since they are unstable to general relativistic effects before the hydrogen burning stage and smaller stars are excluded to avoid overenrichment of metals (Carr, Bond and Arnett, 1983). Very low mass stars do not contribute to the enrichment but are also excluded since their contribution to the background in the optical band would exceed the observed upper limit (Dube, Wicks and Wilkinson, 1979) unless they were too small to generate an appreciable IR density.

For a VMO with $M>200M_\odot$, $L=1.3\cdot10^{38}(M/M_\odot)$erg s^{-1} and the radiation spectrum is black-body with $T_S=10^5$K. If they all form at the same redshift $z_\star$, their radiation will be generated at that epoch providing their main-sequence time ($t_{MS}=2\cdot10^6$y) is less than the expansion time, which requires $z_\star<300h^{-2/3}$. The background energy density can then be estimated. In terms of the parameter $\Omega_R(\nu)\equiv4\pi\nu i(\nu)/\rho_{cr}c^2$ (where $i(\nu)$ is the flux per unit frequency interval), we get

$$\Omega_R(\nu) = 6.2\cdot10^{-4}\left(\frac{f_bX_0}{0.6}\right)\left(\frac{\Omega_\star}{1+z_\star}\right)\left(\frac{x^4}{e^x-1}\right) \tag{1}$$

where $x=h\nu(1+z_\star)/kT_S$, f_b is the fraction of hydrogen burnt to helium and X_0 is the initial hydrogen abundance; $f_bX_0\simeq0.6$ for a VMO with $X_0=0.75$ (Bond, Arnett and Carr, 1983).

By fitting the estimate given by (1) with the data points (see Fig. 1), the values of z_* and Ω_* required are found to be in the ranges: $z_*=38\sim140$ and $\Omega_* h^2=1.0\sim3.8$. Although these values for Ω_* may not conflict with the upper limit permitted by measurements of the cosmological deceleration parameter, they are marginally too large for the dark matter in halos or clusters. Also, since Ω_* should not exceed the nucleon density at the nucleosynthesis era, they are apparently too large to be consistent with the cosmological origin of deuterium (Schramm, 1983).

In some circumstances, one might expect the spectrum to be cut off below $\lambda_i \approx 0.12(1+z_*)\mu$ because of absorption by the ambient hydrogen gas. However, the background ionization expected may be too high to cause absorption unless the gas has a large clumpiness factor. If the spectrum *is* cut-off at λ_i, it is crucial whether the stars form over an extended redshift range. If they do not, and if $t_{MS} \ll t_*$, then the spectrum is too steep to fit the data points as shown by curve (c) in Fig. 1. On the other hand, if the stars form over an extended range of redshifts (z_1 to z_2), then the Lyman-α density would dominate the background for $0.12(1+z_1)\mu>\lambda>0.12(1+z_2)\mu$. In this case, we need $z_1>41$ and $z_2<11$ in order to cover the observed range of the spectrum. If the stars are assumed to form at a rate $\phi(z)$ in units of ρ_{cr} per redshift interval, then the Lyman-α density is

$$\Omega_\alpha(\nu) = 0.004\phi(z=\nu_\alpha/\nu-1)\left(\frac{X_0 f_b}{0.6}\right)\left[\int_{x_i}^{\infty}\frac{x^2 x_\alpha dx}{e^x-1}\Bigg/\int_0^{\infty}\frac{x^3 dx}{e^x-1}\right]$$

$$= 1.2\cdot10^{-3}\phi(z(\nu)) \ . \tag{2}$$

By choosing $\phi(z)$ suitably, one could in principle fit any set of data points, as shown in Fig. 1. In this way one can reduce the required value of Ω_* slightly because z is lower.

THE BACKGROUND GENERATED BY BLACK HOLES

We now examine the radiation generated by black hole accretion. If the holes accrete at the Bondi rate and radiate with an efficiency ε, each one should have a luminosity

$$L = 1.1\cdot10^{32}\varepsilon M^2 n_g T_4^{-3/2} \text{ erg s}^{-1} \ , \tag{3}$$

where the hole mass M is in $M_\odot$ and n_g and T_4 are the density (in cm^{-3}) and the temperature (in 10^4K) of the accreting gas (Carr, 1981). The ambient gas will be heated by the accretion radiation and this will reduce both the accretion rate and the radiation flux. Through this feedback connection one can expect an equilibrium state to arise. The radiation spectrum will be crucial to determining this state.

We take the disc accretion model and assume a "soft" spectrum of black-body form. This may be appropriate for the low luminosity case, $L<0.02M_6^{-1/8}L_{ED}\varepsilon$ (Eardley and others, 1978); here L_{ED} is the Eddington luminosity and $M_6 \equiv M/10^6M_\odot$. For a larger luminosity, the spectrum will be "hard", extending up to the MeV range. It has been suggested that the X-ray background may be the redshifted radiation of such "hard" spectrum holes (Boldt and Leiter, 1981; Carr, 1980; Liang, 1980; Hayakawa, 1982). Here, we identify the "soft" spectrum holes as the sources of the IR background. We note however that, if the energy contained in the "soft" and "hard" parts of the spectrum were comparable, the X-ray background observations would exclude this possibility.

For a black-body spectrum, the presently observed temperature should be

$$T_{bb}^{obs} = (1+z)^{-1}\left(\frac{L}{4\pi R_i^2 a}\right)^{1/4} = 2.1\cdot10^4\{\varepsilon\Omega_g h^2(1+z)^{-1}\}^{1/4}T_4^{-3/8} \text{ K} \ , \tag{4}$$

where Ω_R is the background gas density and we take $R_i=10GM/c^2$ as the inner edge of the accretion disc. We note that T_{bb} is much smaller than the T_s of a VMO and it is independent of M. The present energy density is

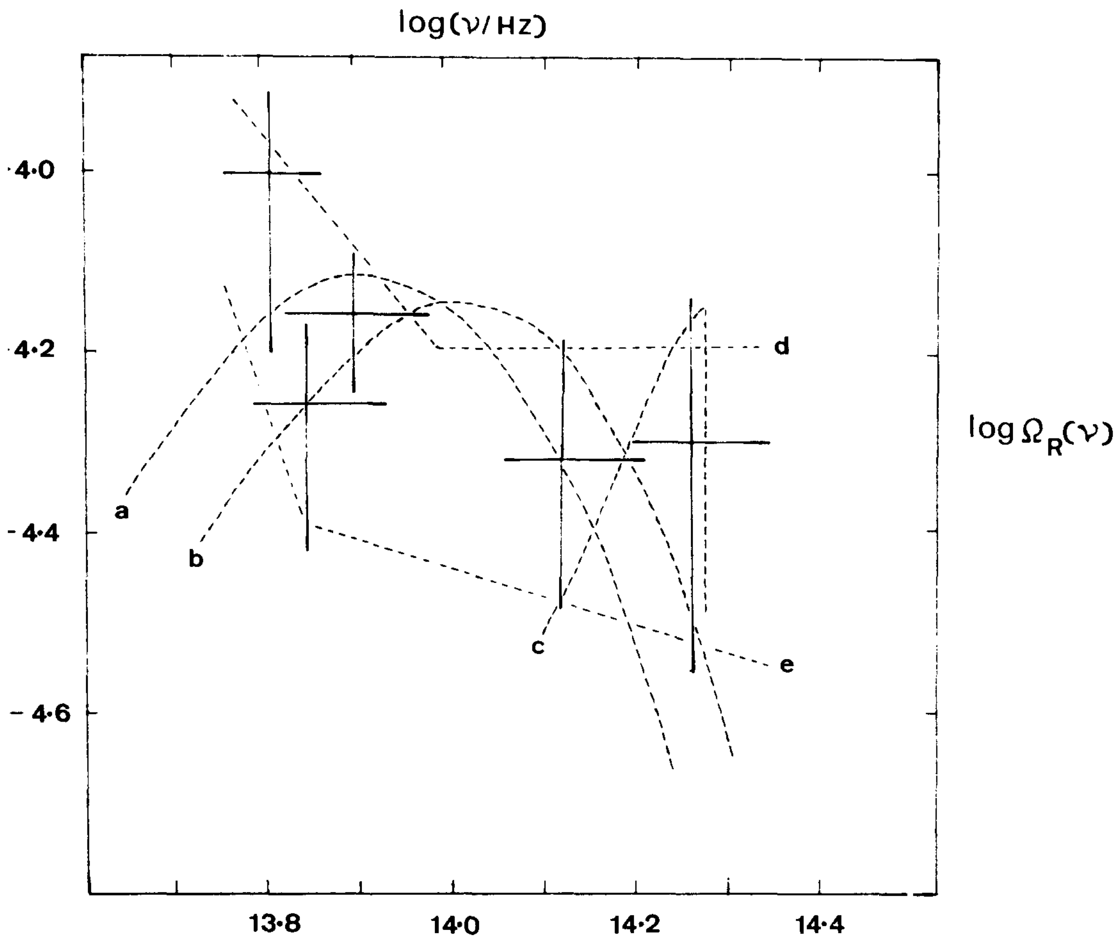

Fig. 1. The observed IR data points are represented in terms of the parameter $\Omega_R(\nu)$ defined in the text. Curves (a) and (b) are drawn from Eq.(1), taking $z_*=100$, $\Omega_*=2.6h^{-2}$ and $z_*=75$, $\Omega_*=1.7h^{-2}$, respectively. Curve (c) is an example of a spectrum with a cut-off at λ_i and $z_*=17$, $\Omega_*=1.2h^{-2}$. If the stars form over a range of redshifts and the spectrum is cut-off at λ_i, the Lyman-α density is given by Eq.(2). Curves (d) and (e) correspond to the maximum and minimum energetic requirements. These curves require $\Omega_*=1.7h^{-2}$ and $0.8h^{-2}$, respectively.

$$\Omega_R = 8\cdot 10^{-5}\varepsilon M_6 \Omega_B \Omega_g \Omega^{-1/2} (1+z)^{1/2} T_4^{-3/2}\ h\ , \tag{5}$$

where Ω_B is the density of the holes and Ω is the total cosmological density.

Since the cooling by line emission and Compton scattering increases rapidly for $T>10^4$K, T should be in the range $10^4\text{K}\sim 10^5\text{K}$. If the gas temperature is bounded like this, a "soft" spectrum accretion phase will be realized only at redshifts $z<z_{bb}$, where

$$1 + z_{bb} = 17 M_6^{-3/8}\ \Omega_g^{-1/3}\ T_4^{1/2}\ h^{-2/3}\ . \tag{6}$$

In order to ensure $z_{bb}>z_g$ (the epoch of galaxy formation), we need

$$M < 3\cdot 10^7 (\Omega_g/0.1)^{-0.9} (1+z_g/10)^{-2.7} T_4^{0.3}\ h^{-1.8}\ M_\odot\ . \tag{7}$$

For $M>10^8 M_\odot$, the holes will never have a "soft" spectrum stage in the pregalactic era. On the other hand, for $M<10^6 M_\odot$, the contribution to Ω_R is much smaller than 10^{-4}.

DISCUSSION

Since Ω_* has to originate from the nucleon density, the starlight model cannot be consistent with the conventional hot big bang scenario. Although this may not apply in the black hole model, since Ω_B need not derive from nucleons in some circumstances, it is difficult to form black holes with $M=10^6\sim 10^8 M_\odot$ by $z\sim 10$ in the usual adiabatic fluctuation scenario. However, if there were isothermal fluctuations or if the universe were dominated by cold particles like axions, then such black holes may form. The pregalactic universe has two spectral windows where it is optically thin (Sato, 1968): one in the X-ray band and one below the Lyman limit. Therefore, if the black holes form before z_{bb}, they will contribute to both windows successively. But if they form after z_{bb}, they may contribute only to the IR window. It should be stressed that the radiation spectrum from accretion discs is difficult to estimate and we have just assumed a soft black-body spectrum for simplicity.

Lastly, we comment on the idea that pregalactic stars and black holes could contribute to the 3K background (Hayakawa, 1983). One of the reasons for this proposal is that one would expect these objects to generate a background density of the order of $\Omega_R\sim 10^{-4}$ if they provide the dark matter. However, the existence of a background in other wavebands with this density may actually make this proposal less plausible.

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