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The Cosmic Near Infrared Background: Remnant Light From Early Stars

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Abstract. The redshifted ultraviolet light from early stars at $z \sim 10$ contributes to the cosmic near infrared background (NIRB). We present detailed calculations of its spectrum with various assumptions about metallicity and mass spectrum of the early stars. We show that if the NIRB has a stellar origin, metal-free stars are not the only explanation of the excess NIRB; stars with significant metals (e.g., $Z=1/50 Z_\odot$) can produce the same amount of background intensity as metal-free stars. This is because the average intensity at 1-2 microns is determined by the efficiency of nuclear burning in stars, which is not very sensitive to metallicity. We predict $v_* I_V / \dot{\rho}_* \sim 4 - 8 n W m^{-2} sr^{-1}$, where $\dot{\rho}_*$ is the mean star formation rate at $z=7-15$ (solar masses per year per cubic megaparsec) for stars more massive than 5 solar masses. On the other hand, since we have very little knowledge about the form of the mass spectrum of early stars, the uncertainty in the average intensity due to the mass spectrum could be large. An accurate determination of the near-infrared background allows us to probe the formation history of early stars, which is difficult to constrain by other means. While the star formation rate at $z=7-15$ inferred from the current data is significantly higher than the local rate at $z<5$, it does not rule out the stellar origin of the cosmic near-infrared background. In addition, we show that a reasonable initial mass function, coupled with this star formation rate, does not overproduce metals in the universe in most cases and may produce as little as less than 1% of the metals observed in the universe today.

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INTRODUCTION

When and how was the universe reionized? This early stage of the universe is hard to study, however, the Near Infrared Background (NIRB) may provide information about this early stage of the universe and the first stars. The logic is very simple: suppose that most of reionization occurred at, say, $z = 9$. The ultraviolet photons ($\lambda \sim 1000 \text{ \AA}$) produced at $z = 9$ during reionization will then be redshifted to the near infrared regime ($\lambda \sim 1 \text{ \mu m}$). In other words, a fraction of the NIRB (whether or not observable) *must come from the epoch of reionization*, and there is no question about the existence of the signal. (Of course the existence of the signal does not immediately imply that the signal is actually significant.) It is therefore extremely important to understand the near infrared background in the context of redshifted UV photons and examine to what extent it is relevant to and useful for understanding the physics of cosmic reionization.

Has it been detected? All of the theoretical proposals were essentially motivated by the current measurements of the NIRB, which suggests the existence of an isotropic background after subtraction of the zodiacal emission [3, 5, 15, 16, 2, 9, 7]. Since the zodiacal emission is ~ 3 times as large as the inferred isotropic component, one should generally be careful when interpreting the data.

The most intriguing feature of the current observational data is that the inferred background seems too large to be accounted for by the integrated light from

galaxies ([14], Figure 12 of [9] and references therein for the compilation of the galactic contribution). It is thus tempting to speculate that the bulk of the NIRB (aside from the zodiacal light) actually comes from stellar sources at the epoch of reionization.

STELLAR EMISSION AND REPROCESSED LIGHT

We calculate the background intensity, I_V , as [10]

$$I_V = \frac{c}{4\pi} \int \frac{dz p([1+z]v, z)}{H(z)(1+z)}, \quad (1)$$

where v is an observed frequency, $H(z)$ is the expansion rate at redshift z ($dt/dz = -[H(z)(1+z)]^{-1}$), and $p(v, z)$ is the volume emissivity in units of energy per unit time, unit frequency and unit *comoving* volume. There are several contributions to the emissivity. One is the continuum emission from stars themselves, p^* , which is nearly a black body spectrum, and the others are reprocessed light of ionizing radiation: a star ionizes neutral gas in its neighborhood and a series of recombination lines, p^{line} , emerge. The ionized gas (or nebula) also emits free-free and free-bound continuum emission, p^{cont} , as well as two-photon emission, $p^{2\gamma}$. (See Fernandez & Komatsu [4] for the complete formalism on how to compute the luminosity for each of these components). The volume

emissivity is

$$p(\nu, z) = \dot{\rho}_*(z) c^2 \sum_{\alpha} \langle \epsilon_{\nu}^{\alpha} \rangle, \quad (2)$$

where

$$\langle \epsilon_{\nu}^{\alpha} \rangle \equiv \frac{1}{m_*} \int dm m f(m) \left[\frac{\bar{L}_{\nu}^{\alpha}(m) \tau(m)}{m c^2} \right], \quad (3)$$

and $f(m)$ is the mass spectrum, $\dot{\rho}_*$ is the star formation rate, m_* is the mean stellar mass of the mass function, τ is the stellar lifetime, and $\bar{L}_{\nu}^{\alpha}$ is the luminosity for the radiative process α .

The mass spectra that were used were Salpeter [12], Larson [8] (which matches Salpeter's in the limit of $m_c \rightarrow 0$, and one can explore a variety of models by changing one parameter, m_c). We shall assume $m_c = 50M_{\odot}$, and a top-heavy spectrum. Two stellar metallicities were modeled: metal free stars ($Z = 0$) and metal-poor stars ($Z = 1/50Z_{\odot}$).

ENERGY BUDGET

We calculate a spectrum of radiative efficiency averaged over the mass spectrum. Figure 1 shows $\nu \langle \epsilon_{\nu}^{\alpha} \rangle$ for the stellar, nebular continuum (free-free and free-bound), Lyman- α , and two-photon emission. Metallicity changes hardness of the stellar spectrum: the harder the spectrum is, the more the ionizing photons are emitted, and thus the more the Lyman- α and two-photon emission emerge. This explains why the metal-free stars have much more energy in Lyman- α and two-photon emission than in stellar emission. On the other hand, the metal-poor stars have more energy in stellar emission. For the same reason, heavier mass spectra tend to produce more energy in Lyman- α and two-photon emission than in stellar emission. In both cases, however, the total radiative efficiency is about the same: $\nu \langle \epsilon_{\nu} \rangle \sim 10^{-3}$. This is merely an approximate conservation of energy: initially all the energy was generated by nuclear burning in stars. The generated energy is then radiated or reprocessed, but the sum should be more or less the same as the input energy. This property makes the prediction of the NIRB very robust, up to an unknown star formation rate, $\dot{\rho}_*$, which will be constrained by a comparison to the observational data.

SPECTRUM OF THE NEAR INFRARED BACKGROUND

By integrating the volume emissivity over redshift, we obtain the background intensity spectrum in the near infrared from early stars. To do this, however, one needs

FIGURE 1. Spectrum of radiative efficiency, $\nu \langle \epsilon_{\nu} \rangle$,

FIGURE 2. Spectrum of the NIRB, $\nu I_{\nu} / \dot{\rho}_*$, for star formation from $z = 7 - 15$ with various assumptions about metallicity and initial mass spectrum.

to specify the evolution of star formation rate over time, $\dot{\rho}_*(z)$, which is unknown. Therefore, for simplicity, we shall assume that the star formation rate is constant over time, at least for the redshift range of interest. In other words, we calculate the intensity spectrum for a given “time-averaged” star formation rate. Figure 2 shows $\nu I_{\nu} / \dot{\rho}_*$ for stars in the redshift $z = 7 - 15$. Within $1 - 2 \mu\text{m}$, the intensity is dominated by Lyman- α emission. For metal poor stars, there is also a significant contribution from stars themselves, which brings the overall intensity for metal poor and metal free stars to be about the same. This seems striking, but is merely a consequence of an approximate energy conservation. Therefore, the predicted intensity is not sensitive to stellar metallicity.

IMPLICATIONS FOR THE COSMIC STAR FORMATION RATE

Comparing the predicted values of $\nu I_\nu / \dot{\rho}_*$ to the measured data, we can constrain the star formation rate $\dot{\rho}_*$. The NIRB has been determined with various satellites, such as the Diffuse Infrared Background Experiment (DIRBE) on the Cosmic Background Explorer [6, 1] and the Near Infrared Spectrometer (NIRS) on the InfraRed Telescope in Space (IRTS) [9]. A significant uncertainty exists in the observational data, largely because of uncertainty in subtraction of the zodiacal emission. One may summarize the current measurement of the cosmic NIRB as $\sim 2 - 50 \text{ nW m}^{-2} \text{ sr}^{-1}$ from $1-2 \mu\text{m}$, which includes the $1-\sigma$ lower bound of the lowest measurement and the $1-\sigma$ upper bound of the highest measurement. Taking into account a scatter in theoretical predictions due to different assumptions about metallicity and initial mass spectrum, we obtain $\dot{\rho}_* \sim 0.3 - 12 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z = 7 - 15$. (Note that the error bar is not dominated by theory but by observational errors.) It should be emphasized that even if the observations of the NIRB change and become more precise, this method will still put upper limits on the star formation in the early universe.

A more recent study by Thompson et al. [13] shows that the Near Infrared Background excess might be much smaller than these values. By subtracting the median background, they were able to remove the isotropic component that could be due to zodiacal light. The excess they found was $0.0^{+3}_{-0.3} \text{ nW m}^{-2} \text{ sr}^{-1}$. Their method would miss any components of the NIRBE which is flat on scales of $100''$ or clumped on scales of several arcminutes. These numbers can also lead to constraints on early star formation - if we use their upper limit of $3 \text{ nW m}^{-2} \text{ sr}^{-1}$, the upper limit of the star formation rate in the early universe would be $\dot{\rho}_* \sim 0.38 \text{ to } 0.72 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z = 7 - 15$, depending on stellar mass spectrum.

An important cross-check is to see if this star formation rate overproduces the metals in the IGM. We can assume that the transition from metal-free to metal-poor stars occurs at $Z = 10^{-4} Z_\odot$. After this metallicity is reached, metal poor stars begin to form. If this transition happened before a redshift of 15, all of the NIRB is from metal poor stars, and the maximum amount of metals would be produced. We take the upper limit of metals that can be produced in the universe to be the solar metallicity. The metals produced by a stellar population is given by

$$\rho_{\text{metals}} = \frac{\rho_*}{m_*} \int_{m_1}^{m_2} f(m) M_{\text{metals},ej}(m) dm \quad (4)$$

where ρ_{metals} is the mass density of metals from a population of stars, ρ_* is the stellar mass density, and $M_{\text{metals},ej}$ is the mass of metals ejected from a star, and

were modeled from the metal yields in [11]. The maximum metal mass density that can be produced is then $\rho_{\text{metals}}^{\text{max}} = 1.2 \times 10^8 \text{ M}_\odot \text{ Mpc}^{-3}$. If the predicted metallicity from Eq. [4] exceeds this value, the model must be ruled out. We have found that a population of metal poor stars do *not* overproduce metals that we observe in the universe today, except for the Larson mass function upper $1 - \sigma$ value for the star formation rate.

CONCLUSIONS

We have presented detailed theoretical calculations of the intensity of the cosmic NIRB from early stars. We have shown that the intensity is essentially determined by the mass-weighted mean nuclear burning energy of stars (for a given mass spectrum of early stars) and the cosmic star formation rate. The prediction is not sensitive to stellar metallicity. The inferred star formation rate is $\dot{\rho}_* \sim 0.3 - 12 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z = 7 - 15$ for $m > 5 \text{ M}_\odot$. In addition, the derived star formation rate does not overproduce metals in the IGM, producing as little as less than 1 % of the metals in the IGM.

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