A POSSIBLE FOREST OF EMISSION LINES FROM PROTO-GALAXIES

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Summary

The possibility of detecting proto-galaxies in the UV band is pointed out, assuming galaxy formation occurred at \( z \approx 5 - 6 \). It is shown that the diffuse gas in collapsing galaxy sized objects with temperatures \( \sim 10^{6.5} \pm 0.5 \) K, and with a modest amount of metallicity, should copiously produce emission lines from highly ionized Iron atoms. The expected luminosity from models of galaxy formation is compared with the sensitivity of HST.

Keywords: Cosmology –theory; Galaxies–formation.

1. Introduction

The search for galaxies at birth is one of the central goals of modern observational cosmology. The work of Partridge and Peebles (1967) was among the first theoretical studies on how galaxies might appear at their forming stage. They calculated the luminosity of galaxies in hydrogen Ly\( \alpha \) when the bulk of their stars were forming at \( z \approx 10 - 30 \) and predicted their appearances as diffuse red objects. Meier (1976) found the hydrogen Ly\( \alpha \) luminosity to be of the order of \( \sim 10^{41} \) ergs/s and that these objects would appear blue at much lower redshifts. Other studies on the possible appearances of proto-galaxies, from various mechanisms for emission, have in general resulted in such order of magnitude of brightness or bigger. Shull and Silk (1979) considered emission from supernova remnants inside proto-galaxies in UV wavelengths. Baron and White (1987) considered models of dissipative collapse resulting in slow star formation and, thus, with dimmer and more extended appearances. Various authors have also calculated the radiation from the dust from primeval star formation in infrared wavelengths. A recent paper that reviews various aspects of the observability of proto-galaxies is that of Djorgovsky and Thompson (1992)(hereafter referred to as DT92).
Observers usually consider the phase of the bulk of star formation as defining the galaxy formation phase. However, the continuum radiation from star formation is expected to be relatively flat (except for the Lyman break at 912 Å), and, therefore, lacking any information about the redshift. One then looks for emission line signatures, such as, hydrogen Lyα. A variety of Lyα objects have already been discovered at moderately high redshifts ($z \sim 1.8 - 3.8$), but their identification as genuine forming galaxies is suspect because most of them seem to be associated with AGN sources (DT92).

One uncertainty in searches for proto-galaxies lies in selecting the wavelength for detection and stems from our ignorance of the epoch of galaxy formation. Though the above mentioned objects (at $z \sim 2 - 3$) intrigue us with the possibility of being real proto-galaxies, studies suggest that at least some fraction of these systems formed at $z > 5$ (Hamilton (1985), Gunn et. al (1986)). Moreover, the existence of a large number of radio galaxies at $z > 3$ and the absence of a sharp quasar number density cut off out to $z \sim 5$, argue for a higher galaxy formation redshift than has been searched so far (i.e., $z \lesssim 5$).

Here we consider the possibility of a definite spectral signature from highly ionized Fe atoms in the diffuse gas inside forming galaxies. It is very likely that the diffuse gas in the proto-galaxies, possibly coexisting with the first stars and hence with some metalicity, reached temperatures of the order of $10^6 \pm 0.5 K$, either from virialization due to the gravitational potential of the halo or because of some other mechanisms. In that case, as we show later, various emission lines of Fe atoms stand the chance of being the most luminous ones and of giving specific information about the redshift.

We begin by stating our assumptions and indicating the motivations for considering temperatures in the range $\sim 10^{6.0 \pm 0.5} K$ for the gas.

2. Luminosity in Fe lines

(a) Temperature of the diffuse gas: For simplicity we assume an $\Omega = 1$ and $h = 1$ universe. Consider a cloud of gas inside the halo of dark matter. If we assume that the halo of dark matter can be modeled as a spherically symmetric isothermal sphere (of temperature $T$), then hydrostatic equilibrium yields, $T = 1.44 \times 10^6 \left(\frac{V}{200 \text{ km/s}}\right)^2 K$ (with $\mu = 0.59$). Here, $V_c = (GM(r)/r)^{0.5}$ is the circular velocity.

Thus, if the gas is at the virial temperature of the halo potential, then with the circular velocities of the present day spirals like Milky Way, the temperature would be of the order of $\sim 10^6 K$. Merger of haloes and the subsequent collisions between subgalactic fragments could also have released a large amount of gas at high temperature. Collisions between clouds with velocities $\sim 200 \text{ km/s}$ during the merger event could result in temperatures $\sim 10^8 K$. Moreover, as Shull and Silk (1979) considered, supernova remnants from the first bursts of star formation could lead to high temperatures for the diffuse gas.
(b) *Luminosity*: First we calculate the cooling function of a gas with temperature \( \sim 10^6 \) K due to emission of various atomic lines using the results of Gaetz and Salpeter (1983). The most important lines at this temperature are [Fe VII] \( \lambda \lambda 166.2, 176.9\AA \), [Fe VIII] \( \lambda \lambda 167.9, 168.7, 185.8\AA \), [Fe IX] \( \lambda 171.1\AA \), [Fe X] \( \lambda \lambda 174.5, 178.3, 186.3\AA \), [Fe XI] \( \lambda \lambda 180.7, 189.3\AA \), [Fe XII] \( \lambda \lambda 189.7, 190.1, 194.1, 196.1 \). Collisional ionization equilibrium is expected to hold, and the deviation in the ionization fraction of highly ionized Fe atoms due to non-equilibrium processes negligible for the above range of temperatures (Schmutzler and Tscharnuter 1993). In the possibility of runaway cooling at \( T > 10^6 \) K, if the heating sources continue to keep the gas hot, ionization equilibrium may collapse, but the gas soon reaches a temperature \( \sim 10^6 \) K, where the cooling is maximum. The emission in line photons is more or comparable to that due to thermal bremsstrahlung at these wavelengths for metallicities \( Z \gtrsim 0.075 \) and we only consider the former. The constructed cooling function is shown in fig. 1. Fig. 2 shows the relative intensities of various lines for different temperatures.

If the density profile of the baryonic gas (of radius \( R \)) is taken to be \( n \propto r^{-\alpha} \), with uniform metallicity, one then easily calculates the total luminosity of the cloud of gas in these lines. At \( 10^6 \) K, e.g., one gets, for \( \alpha < 1.5 \),

\[
L_{Fe} \approx 5 \times 10^{44} \left( \frac{M_{\text{gas}}}{10^{10} M_\odot} \right)^2 \left( \frac{Z}{Z_\odot} \right) \left( \frac{1}{\mu} \right)^2 \left( \frac{3 - \alpha}{3 - 2\alpha} \right)^2 \left( \frac{R}{5 \text{kpc}} \right)^{-3} \text{erg/s} \quad (2.1)
\]

As the brightness does not strongly depend on \( \alpha \), we shall use a value of 1. Considering the extent of the cloud till \( R \sim 5 \) kpc, we have calculated the luminosity of a few cases. Smaller values of \( R \) would correspond to higher contours toward the center, but the very central region (\( \ll 1 \) kpc) is likely to be in a very different state of affairs than the outer few kiloparsecs. Thresholds of detection with the FOC camera aboard HST are shown in the \( M_{\text{gas}} - T \) space in fig. 3, for clouds with \( R = 5 \) kpc. The filter F140W with \( \lambda = 1360 \)\AA and \( \Delta \lambda = 298 \)\AA seems to be suitable for the above lines from a redshift of \( z \sim 5 - 6 \). For larger values of \( R \), the integration time to detect the same mass of gas inside \( R \) would scale as \( \sim R^{-6} \).

Intensities of the individual lines, shown in fig. 2, indicate that the most prominent lines contribute to the order of \( 1/2 \) of the total luminosity. Once any candidate protogalaxy has been detected with imaging, then one could integrate longer on such objects in the spectroscopic mode to detect the prominent lines in the forest. As was explained earlier, the spectral signature would bear information about the redshift of its origin. Imaging and subsequent follow up with spectroscopic details could, therefore, result in detection and identification of such proto-galactic objects. Fig. 2 shows that at any temperature there are at least two lines with power \( (\text{erg cm}^3 \text{/s}) \gtrsim 10^{-24} n_en_H (Z = 0.1 Z_\odot) \). The threshold
contours for detecting the prominent lines are shown in fig. 4. After the optics in HST is corrected, the sensitivity is expected to go up and fainter galaxies could be detected then.

The opacity of the lines at the line center can be written as

$$\tau_l = 1.2 \times 10^{-18} X_4 T_6^{-0.5} \theta_i f \lambda_{1000} \mu^{1.5} N$$

$$= 1.8 \times 10^{-19} \left( \frac{Z}{Z_{\odot}} \right) T_6^{-0.5} \theta_i f \lambda_{1000} N$$  \hspace{1cm} (2.2)$$

where $10^{-4} X_4$ is the fractional abundance of the element (here, Fe), $\theta_i$ is the fractional abundance of the ion, $f$ is the line oscillator strength, $\lambda_{1000}$ is the wavelength at line center in units of 1000 Å, and $N$ is the column density. We wrote $X_4 = 10^{-5} \left( \frac{Z}{Z_{\odot}} \right)$ and $\mu = 0.6$ for the second expression above. Larger clouds with $N \sim 10^{22}$ will be marginally opaque to the most dominant lines for $(\frac{Z}{Z_{\odot}}) \sim 0.1$. But the collisional deexcitation rate is not high enough to render the lines thermalized. In the two level atom model, the line cooling function is

$$q = \frac{n_l E_{cl} \exp(-E/kT)}{1+\gamma}$$

where $\gamma_l = 2 n_e c_l (1 + \tau_l) / (A_l)$ is the escape parameter, $A_l$ is the Einstein’s $A$ coefficient, $c_l$ is the collisional deexcitation rate of the line, and $n_l = 10^{-4} X_4 n_e \theta_i$. Using the collision strengths of the lines from Gaetz and Salpeter (1983), one readily finds that for the proto-galaxies, $\gamma_l \ll 1$ and most of the radiation should emerge from the cloud.

3. Comparison with other predictions

We can compare the above luminosity with the predicted luminosities of proto-galactic objects in the literature in different wavelengths. Meier (1976) concluded that a star formation rate of $1.0 \, M_{\odot} \, yr^{-1}$ in a primeval galaxy produces a luminosity, which is approximately constant longward of the Lyman break and is equal to $2.6 \times 10^{27}$ ergs $s^{-1}$ Hz$^{-1}$. For hydrogen Lyα line, this leads to a luminosity of $\sim 6.7 \times 10^{42} \left( \frac{SFR}{1 \, M_{\odot}/yr} \right)$ erg/s. Baron and White (1987) calculated the Lyα brightness of proto-galaxies at redshifts of $z \sim 2$ for CDM model. In their model, the collapse of a galaxy is a highly inhomogeneous process, leading to cloud collisions and star formation behind the shock fronts. Their typical example of a proto-galaxy had two bursts of star formation of $\sim 70, 12 \times 10^9 yr/t_{coll}$ $M_{\odot} \, yr^{-1}$ for a final galaxy with $10^{11} M_{\odot}$ of stars, where $t_{coll}$ is the collapse time of a galaxy.

Shull and Silk (1979) calculated the UV luminosity of proto-galaxies arising from shock heated gas due to supernova remnants following a burst of star formation. With $N_s$ as the rate of supernovae per year and $n$ as the mean density of particles, they calculated hydrogen Lyα luminosity as $3.2 \times 10^{43} n^{-0.5} N_s$ erg/s. Luminosity in the band with $\lambda < 228$ Å, was calculated to be $10^{41} n^{-0.5} N_s$ erg/s, with $N_s = \text{few}$.

5. Discussion on observability
Finally we discuss a few aspects of the observability of these proto-galactic objects in UV.

(a) Number density of objects: Recently White and Frenk (1991) have presented expressions for the fraction of matter which is in haloes of a given circular velocity at a certain redshift in the CDM model. One must note that various nonlinear processes and the effects of mergers are yet to be incorporated in a realistic manner. For a biasing factor $b = 1.5$, haloes with $V_c = 200$ km/s peak at $z = 4$ with a comoving density of $8.4 \times 10^{-4} \text{ Mpc}^{-3}$. At $z = 6$, the corresponding density is $4.4 \times 10^{-4} \text{ Mpc}^{-3}$. The virialized region of these haloes have a mass $1.8 \times 10^{11} \text{ M}_\odot$, and radius 76.1 kpc (baryons would be concentrated toward the center). They defined virialized part of the halo as the region within which the mean overdensity is 200.

The comoving volume can be written as $V = 4 \left( \frac{c}{H_0} \right)^3 (1 + z)^{-1.5} [1 - (1 + z)^{-0.5}]^2 \theta^2 \Delta z$ for $\Omega = 1$. For $z = 5$, this gives $V \sim 2.175 \times 10^2 \theta^2 \text{(arcmin)} \left( \frac{\Delta \lambda}{\lambda} \right) (h^{-1} \text{Mpc})^3$. Turning this over, a comoving density of $4.4 \times 10^{-4} \text{ Mpc}^{-3}$ means $\sim 0.1$ haloes per arcminute square, for $[\Delta \lambda] \sim 1$ and $h = 1$. It is a small number but not prohibitively low (the field of view of FOC in F/48 mode is $\sim 0.5$ arc minute square).

In the HDM model and the explosion scenario, galaxies form earlier than in CDM model. In the explosion model, the expanding shells would have been detectable in UV but for their large size. The intensity per unit area would be too small to be detected.

(b) Effect of Dust: It has been suggested that the reason for null detection of proto-galaxies in recent Lyman $\alpha$ searches is obscuration by dust in those objects. However, Djorgovski and Thompson (DT92) have used the COBE limit on the sub-mm background to argue against completely obscured star formation. Furthermore, York and Meyer (1989), and Fall et. al (1989) found that distant damped Lyman $\alpha$ systems are both dust and metal poor (also see Pettini et. al (1990)). van den Bergh (1990) concluded that the effect of dust should not be important as long as $[Fe/H] \lesssim -1.0$.

(c) Intervening clouds: Absorption by intervening clouds with high column density is probably the most worrisome aspect concerning observability of the Fe emission lines in the UV. Lyman $\alpha$ clouds, with a column density in HI $\gtrsim 10^{18}$ cm$^{-2}$, are numerous and perhaps cover a significant portion of the sky. It has been estimated (Sargent 1987) that 50% of randomly chosen lines of sight intercept a cloud which absorbs 99% or more of the flux at the Lyman limit at a redshift of $z = 2$. The fraction rises to 90% by a redshift of $z = 4$. The chance, therefore, of discovering proto-galaxies at high redshift in UV may appear to be slim, but considering the importance and novel impact of such a discovery, such a search would seem to be worthwhile.

Conclusions
We find that photons from highly ionized Fe atoms in the diffuse gas in collapsing galaxies, with temperatures $\sim 10^{6 \pm 0.5}$ K, should be detectable at redshifts $z \sim 5 - 6$ in the UV by HST with a few hours of integration. We suggest spectroscopic follow up of the candidate objects from imaging which would elicit emission lines fixing the redshift of their origin.

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Figure 1. Cooling function for the Fe lines referred to in the text for $Z = 0.1 Z_\odot$. $P_{n_e n_H}$ is the power radiated per unit volume of the gas. Collision strengths for individual lines are taken from Gaetz and Salpeter (1983) and equilibrium fractional abundances for different ions from Shull and Van Steenberg (1982).

Figure 2. Relative intensities of individual lines at $T = 10^{5.7}$K (dashed line), $10^6$ K (solid line) and $10^{6.3}$ K (dotted line). Metallicity is that of solar abundance and $P_{n_e n_H}$ is the power radiated per unit volume.

Figure 3: Contours of threshold detection of gas clouds of radius 5 kpc, as functions of redshift, metallicity and temperature. The sensitivity used is that of the FOC aboard HST (integration time 5 hours, $S/N = 5$). Solid and dashed lines refer to metallicities $Z = 0.1, 0.075 Z_\odot$ respectively. Luminosity distance and angular size was calculated for an $\Omega = 1, h = 1$ universe.

Figure 4: Contours of threshold detection of individual lines by F/96 FUVOP with integration time 20 hrs and $S/N = 5$. Radius of gas clouds is taken equal to 5 kpc and metallicity $Z = 0.1 Z_\odot$ in an $\Omega = 1, h = 1$ universe.