Collapse of Primordial Clouds in the Presence of UV Radiation Field

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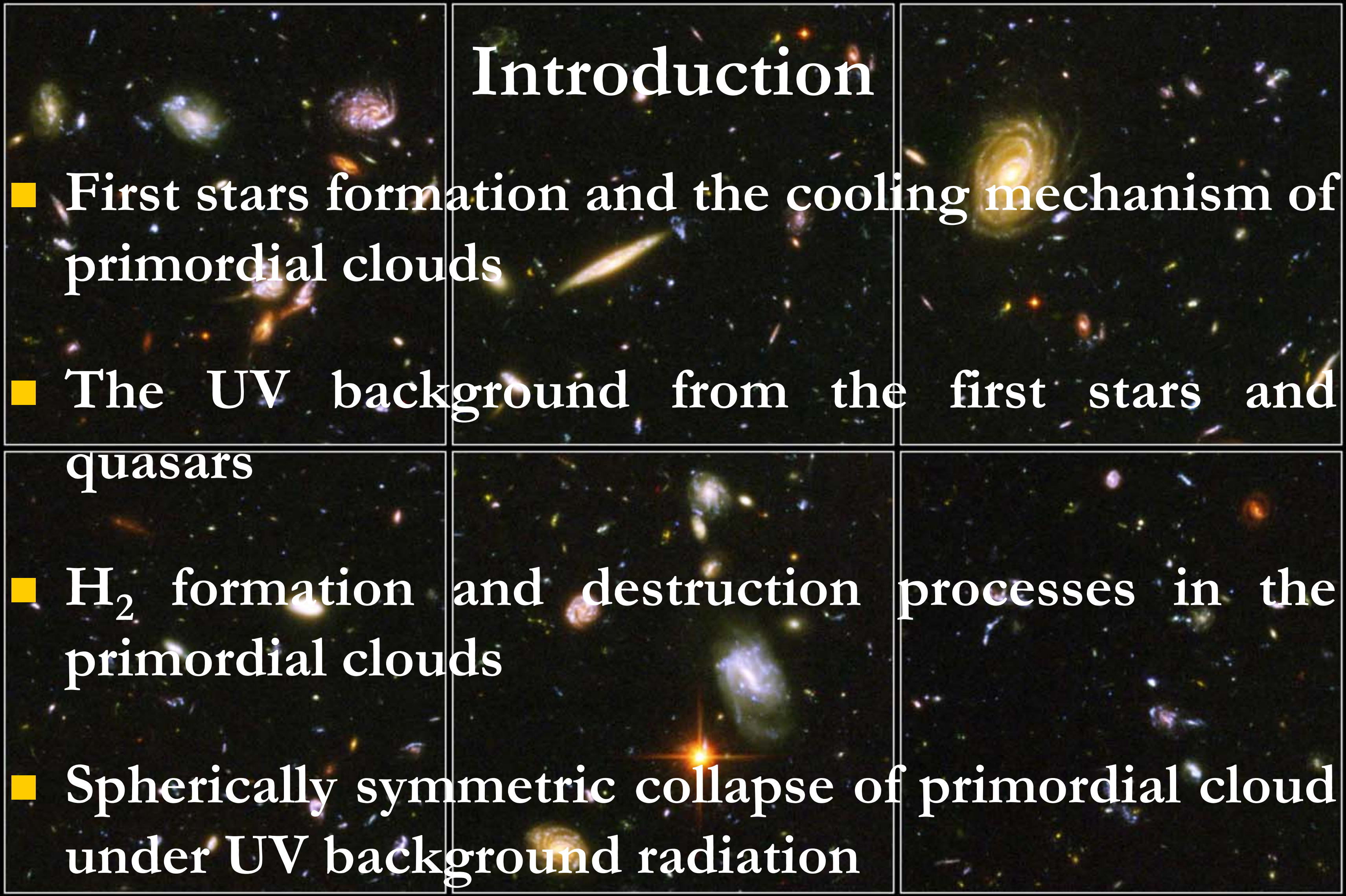
Introduction

- First stars formation and the cooling mechanism of primordial clouds
- The UV background from the first stars and quasars
- H_2 formation and destruction processes in the primordial clouds
- Spherically symmetric collapse of primordial cloud under UV background radiation



Hubble Ultra Deep Field Details
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

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Formation of the first objects in the Universe

The first objects are a direct consequence of the growth of primordial density fluctuations.

- primordial density fluctuations
- decoupling of the perturbation from the Hubble flow
- subsequent collapse
- formation of a virialized cloud (cloud in the hydrostatic equilibrium)

Now we need some cooling mechanism.

- the successive fragmentation and contraction processes

Primordial star formation can be viewed as the successive fragmentation and contraction processes of collapsed cosmological objects.

Cooling mechanism in the metal-free gas clouds

- Large primordial clouds ($T > 10^4$ K, $M > 10^8 M_{SUN}$)
  Emission of the radiation from the excited atomic hydrogen H.

- Small primordial clouds ($T < 10^4$ K, $M < 10^8 M_{SUN}$)
  Emission of the radiation from the excited rotational and vibrational states of H_2 molecules. This mechanism is more efficient in the temperature of the order 100 K.

The presence of initial mass fraction of the molecular hydrogen H_2 of only 10^{-6} is enough for triggering the final collapse of low mass clouds.

Formation of primordial objects has been investigated mainly in the following two contexts:

- first luminous objects (first stars, quasars, globular clusters and proto-galaxies)
  - little influences of the external radiation field except for that of the CMB (the cosmic microwave background)

- ‘second generation objects’
  - largely affected by the external UV radiation produced by „the first luminous objects”

Sources of the UV radiation

- First stars
  - From the detailed 3D simulations of the formation process of the first stars we can conclude that these stars were very massive ($M \sim 100\ M_{SUN}$).
- quasars
- The decay of very massive exotic particles

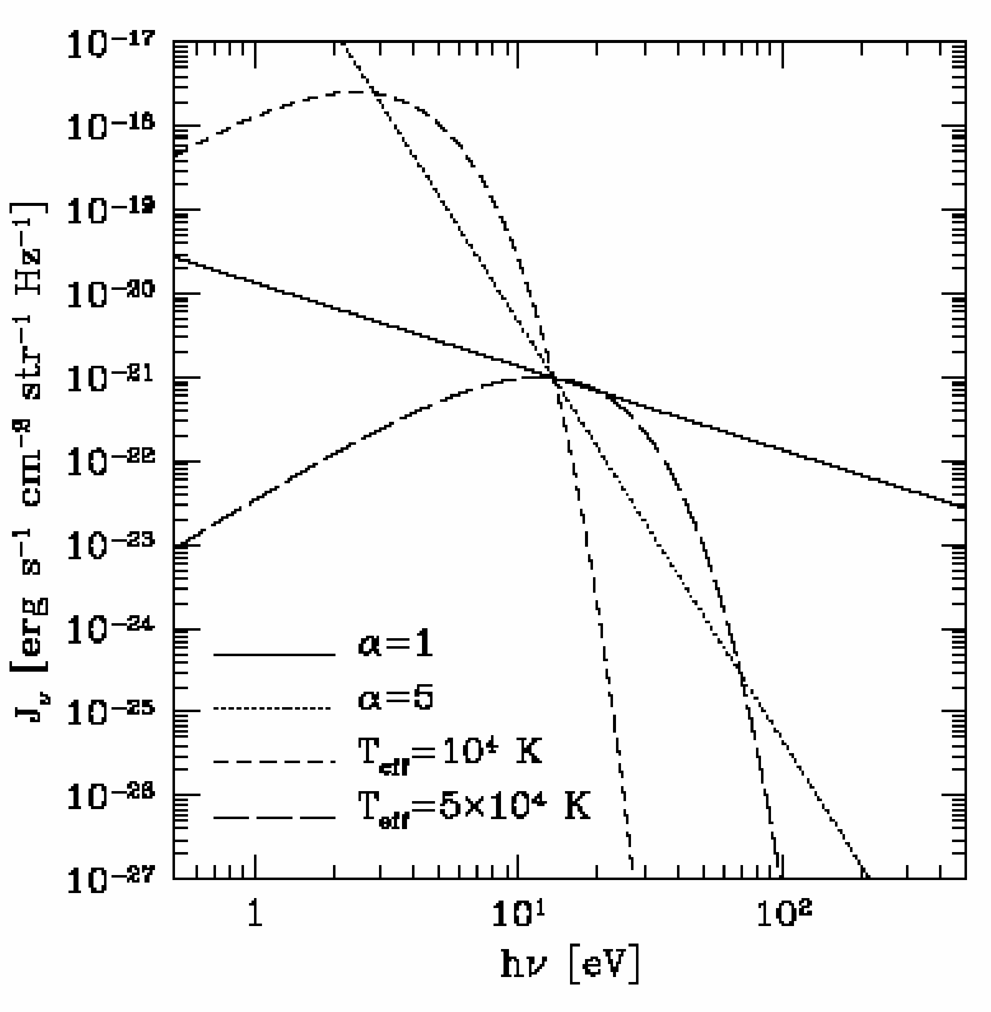
Spectrum of the ultraviolet background

- quasars

$$I_\nu \sim \nu^{-\alpha}$$

- First generation of stars (black body spectrum)

$$I_\nu \sim \frac{\nu^3}{\exp\left(h\nu / k_B T_{eff}\right) - 1}$$



Feedback of the UV background on the star formation

- A key element is molecular hydrogen H_2. In order for stars to form the gas needs to radiate energy efficiently and cool down to temperatures well below $T = 10^4$ K.

- In gas of primordial composition, without metals, cooling processes at this temperature are almost solely dominated by rotational-vibrational line excitation of H_2.

- Formation and destruction of H_2, however, is very sensitive to the presence of a radiation field.

H_2 formation and destruction processes in the primordial clouds

- Production of ***H_2***

$$e^- + H \rightarrow H^- + h\nu \qquad H + H^+ \rightarrow H_2^+ + h\nu$$

$$H^- + H \rightarrow H_2 + e^- \qquad H_2^+ + H \rightarrow H_2 + H^+$$

- Photo-dissociation of ***H_2*** (11,2 < hν < 13,6 eV) (Lyman-Werner bands)

$$H_2 + h\nu \rightarrow H_2^* \rightarrow 2H$$

- Destruction of ***H^-*** and ***H_2^+*** (hν < 11,2 eV)

$$H^- + h\nu \rightarrow H + e \qquad \text{(hν > 0,74 eV (Tegmark, et. al. 1997))}$$

$$H_2^+ + h\nu \rightarrow H + H^+ \qquad \text{(hν > 2,65 eV (Stancil 1994))}$$

Feedback of the UV background on the star formation

- Negative feedback on the star formation (first stars)
  - Dissociation of H2 molecule by photons with energies from the Lyman-Werner bands
  - Destruction of H^- and H_2^+

- Positive feedback on the star formation (quasars, the decay of exotic particles)
  - enhancement of the ionized fraction.

Feedback of the UV background on the star formation

- In addition, self-shielding which takes place during dynamic collapse can also aid H_2 cooling. It means that collapse and star formation in the high-density (more massive) clouds can take place efficiently even under high intensities of the UV background.

- We can see that it is by no means trivial in what circumstances the UVB has positive or negative feedback on star formation in the ‘second generation’ objects.

- **We need the detailed simulation of the collapse of the primordial cloud**

‘Difficulties’ in taking into account the radiation feedback

- Non Local Thermal Equilibrium

the Boltzmann distribution function is not valid

$$\frac{N_u}{N_l} \neq \frac{g_u}{g_l} \exp\left(-\frac{E_{ul}}{kT}\right)$$

- Presence of thousands of H_2 lines

- Solving the radiative transfer equation in order to get correct cooling function

Evolution of spherically symmetric density contrast in the Lambda CDM Universe (Stachniewicz & Kutschera 2001; 2003)

- Equations of dynamic evolution of the dark matter and baryonic gas.

  Cloud is divided into the concentric mass-shells. Simulation is tracing collapse of the individual mass-shells.

$$\frac{dm_B}{dr_B} = 4\pi r_B^2 \rho_B,$$

$$\frac{d^2 r_B}{dt^2} = -4\pi r_B^2 \frac{dP}{dm_B} - \frac{GM\left(< r_B\right)}{r_B^2},$$

$$\frac{d^2 r_{dm}}{dt^2} = -\frac{GM\left(< r_{dm}\right)}{r_{dm}^2}.$$

Evolution of spherically symmetric density contrast in the Lambda CDM Universe (Stachniewicz & Kutschera 2001; 2003)

- Energy equation

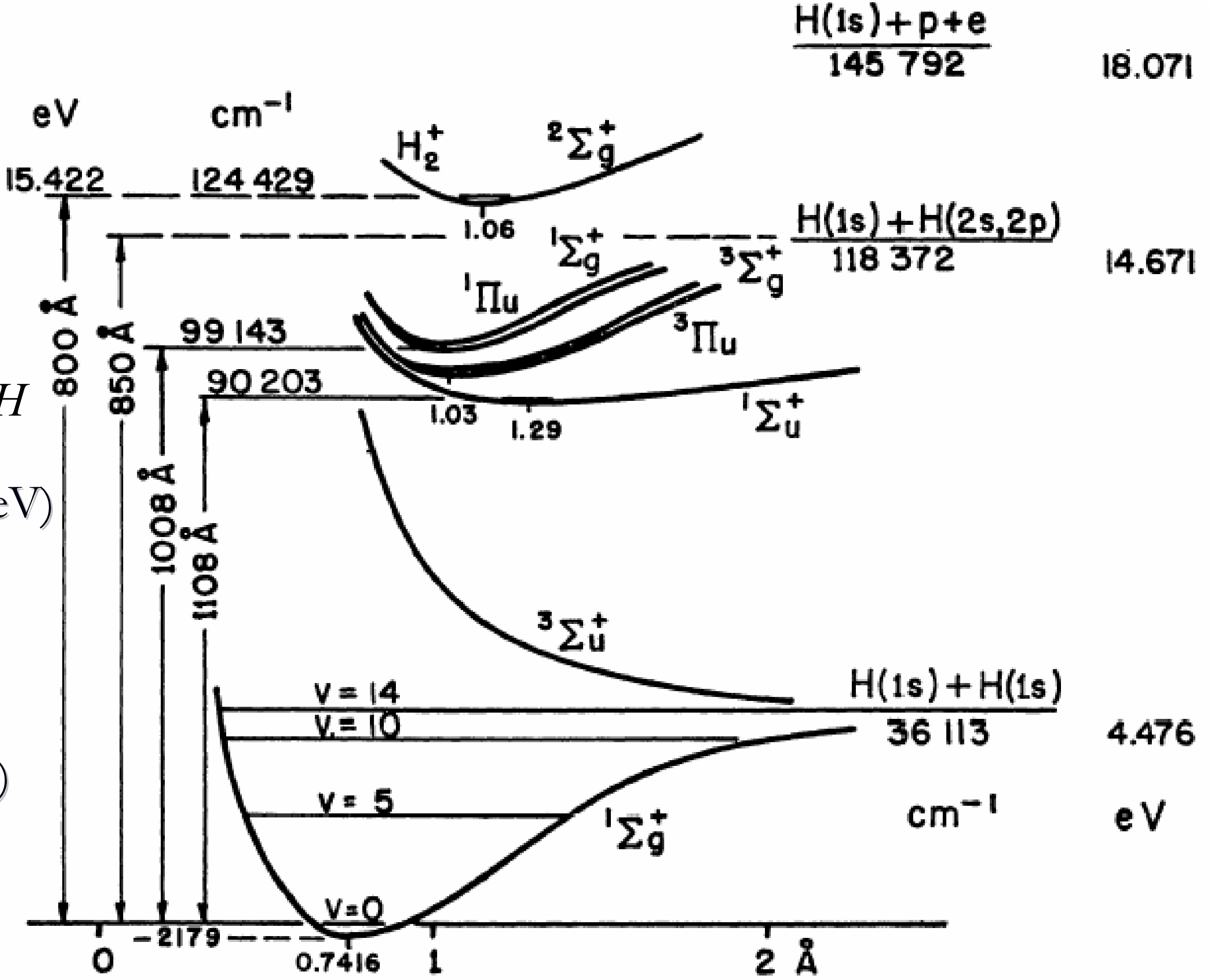
$$\frac{du}{dt} = \frac{P}{\rho_B^2}\frac{d\rho_B}{dt} - \frac{\Lambda_{cool}}{\rho_B}$$

- Equation of state for ideal gas

$$P = (\gamma - 1)\rho_B u = \frac{k_B \rho_B T}{\mu m_p}, \quad \gamma = \frac{5}{3}$$

$(v', J')\ 2p\sigma B^1\Sigma_u^+ \longleftrightarrow (v'', J'')\ 1s\sigma X^1\Sigma_g^+$ **Lyman band**

$(v', J')\ 2p\pi C^1\Pi_u \longleftrightarrow (v'', J'')\ 1s\sigma X^1\Sigma_g^+$ **Werner band**



$H_2 + h\nu \rightarrow H_2^* \rightarrow 2H$

$(11{,}18 < h\nu < 13{,}6\ \text{eV})$

(Field, et. al. 1966)

Transfer equation for spherically symmetric case

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t}+\mu\frac{\partial I_\nu}{\partial r}+\frac{1-\mu^2}{r}\frac{\partial I_\nu}{\partial \mu}=\rho\left\{j_\nu-\kappa_\nu I_\nu\right\},$$

where

- $I_\nu\,(r,\mu,t)\ \left[\frac{erg}{cm^2\,s\,Hz\,Sr}\right]$ - radiation intensity,
- ρ - density,
- κ_ν, j_ν - opacity and emissivity for frequency ν,
- $\mu=\cos\theta\in[-1,1]$,
- θ - angle between radiation direction and radial direction,
- $r\in[r_{min},r_{max}]$ - radius.

If we define „source function”

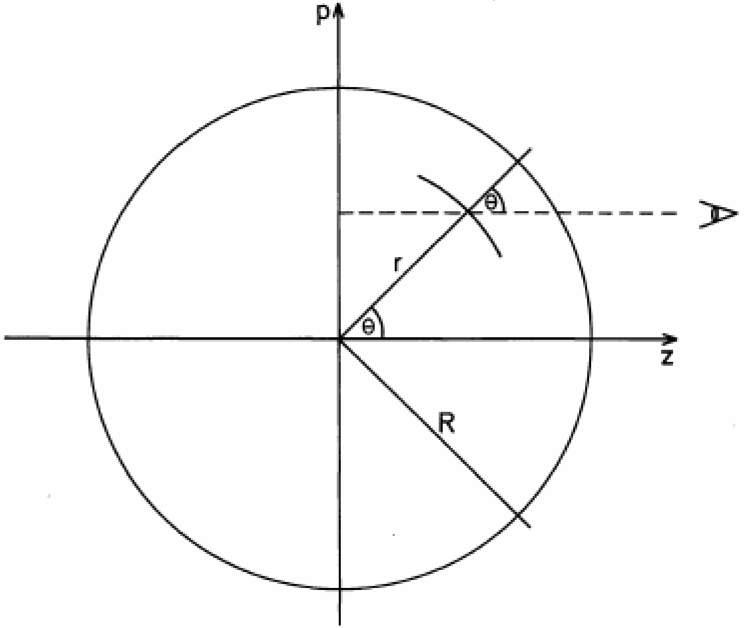
$$S_\nu = \frac{j_\nu}{\kappa_\nu},$$

than transfer equation will be

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mu\frac{\partial I_\nu}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial I_\nu}{\partial \mu} = -\rho\kappa_\nu\left\{I_\nu - S_\nu\right\}.$$

$$I_\nu(r,\mu,t) \to \begin{cases} I_\nu^+(r,p,t) & \mu \geq 0 \\ I_\nu^-(r,p,t) & \mu < 0 \end{cases}$$

$$\begin{cases} \mu\frac{\partial I_\nu^+}{\partial r} = -\rho\kappa_\nu\left\{I_\nu^+ - S_\nu\right\} \\ \mu\frac{\partial I_\nu^-}{\partial r} = \rho\kappa_\nu\left\{I_\nu^- - S_\nu\right\} \end{cases}$$



$$(r,\mu) \to \left(r, p = r\sin\theta = r\sqrt{1-\mu^2}\right)$$

We can define zero, first and second moment of radiation intensity as follows:

$$
\begin{aligned}
J_\nu(r) &= \frac{1}{2}\int_0^1 \left(I_\nu^+ + I_\nu^-\right) d\mu \\
H_\nu(r) &= \frac{1}{2}\int_0^1 \left(I_\nu^+ - I_\nu^-\right) \mu d\mu \\
K_\nu(r) &= \frac{1}{2}\int_0^1 \left(I_\nu^+ + I_\nu^-\right) \mu^2 d\mu
\end{aligned}
$$

$$L(r) = 16\pi^2 r^2 H(r)$$

Eddington factor:

$$f_\nu(r) = \frac{K_\nu(r)}{J_\nu(r)}$$

There are also the zero and first moment equation

$$\begin{aligned} \frac{\partial\left(f_\nu(r)\,J_\nu(r)\right)}{\partial r}+\frac{3f_\nu(r)-1}{r}J_\nu(r)+\rho\kappa_\nu H_\nu(r) &= 0 \\ \frac{\partial H_\nu(r)}{\partial r}+\frac{2H_\nu(r)}{r}+\rho\kappa_\nu^a J_\nu(r)-\rho j_\nu^t &= 0 \end{aligned}$$

If we define

$$q_\nu(r)=\exp\left[\int_{r_c}^{r}\left(3-\frac{1}{f_\nu(r')}\right)\frac{dr'}{r'}\right],$$

than we get

$$\begin{aligned} \frac{\partial\left(f_\nu(r)\,q_\nu(r)\,J_\nu(r)\right)}{\partial r} &= -\rho\kappa_\nu q_\nu(r)\,H_\nu(r) \\ \frac{\partial\left(H_\nu(r)\,r^2\right)}{\partial r} &= r^2\rho\left(j_\nu^t-\kappa_\nu^a J(r)\right). \end{aligned}$$

Two systems of equations

- System I (solved for $f_\nu(r)$ and $q_\nu(r)$)

$$\begin{cases} \mu \frac{\partial I_\nu^+}{\partial r} = -\rho\kappa_\nu \left\{ I_\nu^+ - S_\nu \right\} \\ \mu \frac{\partial I_\nu^-}{\partial r} = \rho\kappa_\nu \left\{ I_\nu^- - S_\nu \right\} \end{cases}$$

- System II (solved for $J_\nu(r)$ and $H_\nu(r)$)

$$\begin{aligned} \frac{\partial \left(f_\nu(r)\, q_\nu(r)\, J_\nu(r) \right)}{\partial r} &= -\rho\kappa_\nu q_\nu(r)\, H_\nu(r) \\ \frac{\partial \left(H_\nu(r)\, r^2 \right)}{\partial r} &= r^2 \rho \left(j_\nu^t - \kappa_\nu^a J(r) \right) \end{aligned}$$

The numerical computational procedure to trace the dynamic evolution of the primordial cloud under the UV background

- We solve the hydrodynamic equations of motion along with equations for energy conservation, ionization, and dissociation of molecular and atomic species.
- We solve the system I equations with the initial value of the source function for f_ν and for q_ν.
- We solve the system II equations for J_ν and H_ν.
- Update the source function and solve the system I once more.
- Iterative procedure between system I and II is continued until convergence.
- After the convergence of the I and II system we calculate luminosity L_ν from the first moment H_ν and than cooling function from luminosity.
- We update abundance of different species and number densities of each atomic and molecular state.

Conclusions

- There is positive and negative feedback of UV radiation to the collapse of primordial clouds and star formation.
- It is by no means trivial in what circumstances the UV radiation has positive or negative feedback on star formation in the 'second generation' objects.
- We need the detailed simulation of the collapse of the primordial cloud
- Collapse and star formation in the high-density clouds can take place efficiently even under high intensities of the UV background.

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