Are young galaxies visible?

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Abstract

- Goal: assess general possibility of observing distant, newly formed galaxies.
- They introduce a simple model of galaxy formation, where the galaxies go through a phase of hight luminosity early in their evolution, at a redshift 10-30.
- The wavelength received from these galaxies today will be in the range $1-3\,\mu$, where detection is difficult, but the Lyman-α line might be detected.
- This experiment could help distinguish between cosmological models.

I Introduction

- Little observational evidence for how/when galaxies were formed and how they evolved.
- Assumption: universe is homogeneous: light from distant galaxies will reveal the past.
- Paper split in two parts: 1) description of how galaxies may have formed/evolved, 2) deriving (from model) the expected properties of young galaxies as they would be observed now.
- Finally: consider possibility of detecting light from these galaxies against the local background.
- Important results of their model:
  1. Young galaxies go through a stage of high luminosity.
  2. The luminosity is $\sim 10^{46}$ ergs/sec in that stage for a galaxy like our own.
  3. The Lyα flux from these galaxies might be 6-7% of total radiation.
- Depending on the acceleration parameter, the optical depth for scattering of light (by electrons) from the young galaxies might reach unity at redshifts z+1 = 5-8, if the dominant mass density in the universe is ionized intergalactic hydrogen (we can not see the galaxies).

II The formation and evolution of the galaxies

a Instability model for the formation of galaxies

- They present a simple picture of galaxy formation so that they can derive the time of formation and luminosity of young galaxies.
- They will focus on the formation of our own galaxy.
- They adopt conventional GR, *without* the cosmological term.
- Their model:
  - In the early universe, the necessary small irregularities in the mass distribution did exist.

- The primordial fireball prevented the formation of stable bound systems until the universe was $\sim 10^5$ years old.
- Galaxies formed due to the gravitational instability of the nearly homogeneous and uniformly expanding distribution of gas that filled the early universe (regions with higher density slow the rate of expansion, and eventually collapse to a bound system).
- Stars would start to form when the systems became so massive that their internal energy was equivalent to 10^4 K (hydrogen can be ionized).
- At the epoch when matter decouples from radiation, the minimum mass required to ionize hydrogen is $10^7\ M_\odot$.
- As the universe expands, the mean density decreases and the minimum mass for ionization increases.
- Stars will tend to remain bound to the system they formed in. Therefore, the protogalaxy must form as a distinct bound system before the stars can have been formed in any great extent.
- In the early stages of collapse for the protogalaxy, turbulence could ionize material and cause density irregularities large enough to initiate star formation.

- This picture has two important consequences: 1) the halo stars preserve some memory of the maximum size of the protogalaxy, 2) the onset of widespread star formation is a well-defined event occurring at an early stage of the initial collapse of a protogalaxy.

b The time of formation of the galaxies

- They use a spherically symmetric model for the formation of the protogalaxy, along with Newtonian mechanics (as the grav. pot. is small):
  - they fix a sphere to the gas, and at early times the radius increases as the gas expands.
  - e.o.m: $\ddot{R}(t) = -GM/R^2$. Solution: eq. (2).
  - t is the proper world time.
  - Solution fixed by 1) very early times the density is uniform, 2) when sphere stops expanding the density is ρ_p.
- Sphere stops expanding: $t_p = (3\pi/32G\rho_p)^{1/2}$, where they have chosen $\eta = \pi$.
- Assuming mass and radius they get $t_p = 1.4 \times 10^8$ years as the minimum value for the formation time of the Galaxy.
- Based on the radius they choose, they must assume that the material in the outer parts of the disk gained angular momentum from the inner parts of the galaxy (if this was not the case, and the angular momentum of each mass element was conserved, it would be that the galaxy collapsed from a larger initial radius, which again would increase the time of formation).
- Starting out with an irregular initial protogalaxy at the maximum point of expansion, they believe that the system could not have collapsed a lot radially before halo stars formed and defined the size of the protogalaxy.
- t_p is a minimum value, but not expected to be larger than a factor 2 at the most.

c Luminosity of the young galaxies: element production

- Two reasons for galaxies having been much brighter before: 1) first generation of stars had many O-B type stars, 2) high luminosity required to account for rapid element production.
- Time from free fall from maximum expansion to highly contracted state: $t_p = (3\pi/32G\rho_p)^{1/2}$. Minimum time at which disk could have formed: $2t_p \geq 3 \times 10^8$ years.
- Lower limit of luminosity of young galaxies from the fact that hydrogen is polluted by material from the first generation halo stars during the initial collapse (the stars must have been active enough to complete heavy-element production): $L_y \geq 3 \times 10^{46}$ ergs/sec.
- The limit comes from eq. (7), where ΔX abundance by mass of all elements created due to hydrogen burning.

d The luminosity of the young galaxies: luminosity function

- Assumption: the first generation of stars in young galaxies was formed with the same distribution of luminosities as the population I stars of the solar neighbourhood.
- Initial luminosity function: number of stars, $\psi(M_v)$, created in each (visual) magnitude interval $[M_v - \frac{1}{2}, M_v + \frac{1}{2}]$.
- In table 1: luminosity function from Limber (1960) + stellar masses and lifetimes.
- Assumption: nearly all the mass of the protogalaxy was rapidly transformed into stars $\rightarrow$ summing column 4 in table 1: calculate luminosity of our galaxy, $L_y = 7.5 \times 10^{46}$ ergs/sec.
- So far, all stars have been assumed to form at substantially the same time. Now the time scale of formation and evolution is taken into account:
  - Massive, short-lived stars contribute most of the luminosity (column 4 and 7 in table 1)
  - Massive stars with $\tau_{MS} < 10^7$ years are as luminous as all the fainter stars combined $\rightarrow$ Did the first stars turn on in periods less than or comparable with 10^7 years?
- From section IIa, the onset of stellar contraction and galactic contraction would have occurred at the same time, based on the assumed model of collapse.
- Various arguments from earlier papers: the interval over which stars began to contract was short compared to 10^8 years.
- The oldest known disk stars show considerable metal abundance $\rightarrow$ a considerable amount of the initial stars must have completed their evolution and added heavy elements to the interstellar gas by the time the disk formed.
- Figure 1: mass bound up in stars vs. luminosity contributed by the stars.
- Very little mass could have been converted to luminosity in times less that $5 - 8 \times 10^7$ years, but the disk is thought to have been formed about 10^8 years after the protogalaxy began to contract.
- $\rightarrow$ the time scale for the onset of stellar formation is a few 10^7 years:
  - It is longer that the lifetime of most luminous stars $\rightarrow$ will determine the duration of the initial bright period in the history of young galaxies.
  - Only a fraction of the most luminous stars would be radiating at any given time (column 8 of table 1). Taking this into account: $L_y \approx 2.5 \times 10^{46}$ ergs/sec.
  - Massive stars formed early will have completed their evolution and returned some matter to the interstellar gas (however, most of this would end up in small stars of negligible luminosity).
- This is all based on hydrogen, and suggests strongly that the model used for star formation does not allow the production of much helium.
- They have ignored how metallicity might affect the contraction time and life-time of the early stars. Also, supernovas will only contribute $\sim 1\%$ of the total luminosity of these galaxies in the bright phase.

e Spectrum

- They determine the qualitative nature of the spectra of young galaxies by the effective temperature of their most luminous stars ~ 30000 K.
- 30000 K $\rightarrow$ black-body spectrum with max $\sim 1000\,\AA$ (a bit flatter around this wavelength irl, because of dim stars). Modifications:
  - *Stellar opacities (especially below the Lyman absorption edge at 912 Å)*: For hot, massive stars there is a Lyman decrement, shown in figure 2. Only hydrogen absorption has been taken into account. From figure 2, about 22% of the flux has $\lambda < 912\,\AA$, and half of this ($\sim 10\%$) escapes the surface of the stars.

- *Interstellar absorption*: If the galaxy is not optically thick to ionizing radiation, the fraction of the ionizing photons absorbed by atomic hydrogen is equal to the ratio of the total rate of production of hydrogen atoms, divided by the rate of stellar generation of ionizing photons. Assuming 10% of the galactic mass to be gaseous hydrogen at 10^4 K, the ratio is 0.001, and most of the ionizing radiation would escape. Therefore, the spectrum of young galaxies would not differ greatly from the assumed stellar spectrum in figure 2. This was assuming that the hydrogen was distributed uniformly over a sphere. If it was distributed in clouds instead, an appreciable fraction of the ionizing radiation would be converted to Lyman photons.

- As much as 10% of the total luminous emission could be in the Lyman lines.
- Figure 3: almost all ionizing photons converted to Lyman photons.The Lyman-α line is shown, but Lyman-β may also be prominent.
- Other possible spectral features: 1) sharp cutoff at Lyman limit due to atmospheric absorption in the bright stars of young galaxies, 2) interstellar helium: line emission at 584 $\AA$.

III Observational parameters of young galaxies

a Redshift

- Assumption: conventional isotropic homogeneous GR model, with $\Lambda = 0$. Energy density in radiation and neutrinos negligible.
- Figure 4: Redshift and epoch of formation of galaxies for three different cosmological models (present mean density).
  1. Mean density $\rho_0 = 7 \times 10^{-31}$ gm/cm^3 = the estimated mass density in galaxies.
  2. Acceleration parameter $q_0 = 1/2$, $\rho_0 = 1.8 \times 10^{-29}$ gm/cm^3.
  3. Acceleration parameter $q_0 = 3$, $\rho_0 = 1.1 \times 10^{-28}$ gm/cm^3 (makes the age of the universe less than the Earth...)
- The two first model preferred over the last, and mostly the second due to philosophical reasons.
- Galaxies brightest at $t \sim 1.5 \times 10^8$ years $\rightarrow$ redshift of young galaxies $10 - 30$.
- Radiation from young galaxies at maximum in UV ($\sim 10^3 \AA$) $\rightarrow$ observed radiation $1 - 3\mu$.

b Surface brightness of the young galaxies

- Expected that young galaxies would be resolvable by a telescope of moderate aperture.
- The photon flux per unit solid angle and wavelength is given by eq. (13), where the wavelength of maximum flux is given by equation (14) for the effective temperature $T_e = 3 \times 10^4$ K. The surface brightness of a galaxy with $L_y = 3 \times 10^{46}$ ergs/sec is given by (15).
- The surface brightness represents quite a large photon flux even for the highest redshifts, but the wavelengths will be arriving in $1 - 3\mu$, which is hard to detect.

c Angular diameters

- The surface brightness is only useful if the galaxies can be resolved $\rightarrow$ figure 5, the angular diameter as a function of redshift for several cosmological models (values of q_0).
- The angular diameter is greater that 5", and can be resolved.
- The observed angular diameter depends on q_0, and could help fix the value.
- Assumption: the galaxies are equally bright at every point on their surface.

d Numbers of young galaxies

- The probability that random line of sight will pass through a highly luminous young galaxy is given by equation (16), and depends upon the geometrical cross-section of the galaxy, the spatial density of galaxies in the present universe, and the redshift at which we are looking.
- Assumption: the galaxies turned on at a time t_p, remained highly luminous for a time Δt and have an effective radius of 15 kpc.
- With a redshift of 10-30, the probability is at least 5%, and if detection is possible, it should not be hard to locate the young galaxies.

IV Is a search for young galaxies possible?

a Observational assessment

- Problem with observing young galaxies from ground: night glow of atmosphere, especially in the infrared region.
- Figure 6: The brightness of the night sky. This will vary with latitude and season (and the values in the figure may be in error by 50-100%). In the near-infrared, from 0.7-1.6μ, the situation is dominated by OH band emission and water-vapor absorption.
- The OH bands originate above most of the atmospheric water-vapor, and will therefore suffer the same absorption as the infrared flux from young galaxies. They therefore compare observed night-sky brightness with the surface brightness of young galaxies corrected for atmospheric absorption.
- Figure 7: Surface brightness of young galaxies is the lower solid line, and the upper solid line is the surface brightness of the young galaxies if 6% of the flux is in the Lyman line. The brightness of the night sky and the zodiacal light is shown in comparison.
- The surface brightness of young galaxies fall below the emission of the night sky for $1+z > 4.5$. If large amounts of the flux come from the Lyman line, the radiation should be detectable for $1 + z < 6$.
- To determine if detection of young galaxies at wavelength 1μ ($z+1 = 8$) is possible, they estimate the signal-to-noise ratio that could be obtained with a telescope of moderate aperture. They find that to distinguish a young galaxy from the night-sky background, an integration time of 5 minutes would be required, for a 36-inch telescope with a band width of $20\mathring{A}$.
- It would be easier to detect young galaxies if we could observe above the atmosphere (as always).
- Based on the model presented in the paper, it is concluded that the search of young galaxies would require a technique capable of detecting signals as small as 10% of the noise.

b Summary

- Purpose: discuss possibility of obtaining observational evidence on the formation of galaxies.
- Experimental problem: detect faint, extended objects at wavelengths $1 - 3\mu$ against the local background.
- Result: The young galaxies could probably not be detected from the ground, but detections appears possible above the atmosphere.
- If discovered, we could say something about the angular size, surface brightness, abundance, distribution and possibly redshift. From this knowledge we could fint the acceleration parameter, q_0, and the epoch of formation of the galaxies.
- It is clear that the young galaxies could not be detected at all unless the luminosity was considerably higher at early epochs that it is today.
- The detection of faint, extended objects in the infrared (identified with young galaxies), would argue strongly for an initial bright phase in galactic evolution.