PROBING THE “DARK AGE” WITH NGST

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Abstract

At redshifts between 5 and 20, stars and 'subgalaxies' created the first heavy elements; these same systems (together perhaps with ‘miniquasars’) generated the UV radiation that ionized the IGM, and maybe also the first magnetic fields. The history of the universe during this crucial formative stage is likely to remain highly uncertain until the launch of NGST.

1 Introduction

The Universe literally entered a dark age about half a million years after the big bang: the primordial radiation then cooled below 3000K and shifted into the infrared. Darkness persisted until the first non-linearities developed, and evolved into stars, galaxies or black holes that lit the Universe up again. Darkness will again gradually descend after $10^{14}$ years, when even the slowest-burning stars have ended their lives (if there has not been a big crunch in the meantime). I won’t be looking that far ahead, But it is important, in discussing NGST, to attempt to forsee what progress will have been made by 2007, and what will still be the key enigmas.

We will by then surely have elucidated the history of star formation, galaxies and clustering back to $z = 5$. The evolution of galaxies of all morphological types will have been clarified by further Hubble Deep Fields, together with follow-up spectroscopy from the new generation of 10 metre telescopes. Also, full analysis of absorption features in quasar spectra (the Lyman forest, etc), will probe the clumping, temperature, and composition of diffuse gas on galactic (and smaller) scales, at least back to $z = 5$.

By 2007 detailed sky maps of the microwave background (CMB) temperature (and perhaps its polarization as well) will offer direct diagnostics of the initial linear fluctuations from which the present-day large-scale structure developed. However, these measurements will not directly probe the small angles that are relevant to the (subgalactic-scale) structures, which, in any hierarchical (‘bottom up’) scenario would be the first non-linearities to develop.

We may by 2007 know the nature of the dark matter, and how it clusters gravitationally; computer simulations will incorporate gas dynamics and radiation in a so-
phisticated way.

But these advances will still leave us very uncertain about the whole era from $10^7$ to $10^9$ years, and about the faint precursors of galaxies – the first stars, the first supernovae, the first heavy elements; and how and when the intergalactic medium was reionized. We will probably still be unable to compute crucial things like the star formation efficiency, feedback from supernovae. etc – processes that current models for galactic evolution are forced to parametrise in a rather ad hoc way.

2 Cosmogonic Preliminaries

Most detailed studies of structure formation have focused on the cold dark matter (CDM) model. Even if its details prove incorrect, it is still a useful ‘template’ whose main features apply generically to any ‘bottom up’ model for structure formation. There is no minimum scale for gravitational aggregation of the CDM. However, the baryonic gas does not ‘feel’ the very smallest clumps: pressure opposes condensation on scales below the baryonic Jeans mass.

Even though the low-mass structures that form first have a higher density than galactic halos that form later, their associate gravitational potential wells are shallower. In contrast to galaxies (virial velocities $\sim 300$ km/sec), and clusters (up to 1000 km/sec) the first structures in which baryons would condense have a scale set by the Jeans mass at the minimum temperature where cooling can occur. Atomic hydrogen cooling is efficient at temperatures above $10^4$K (virial velocities $\gtrsim 10$ km/sec); this yields a characteristic mass of $M = 10^9((1 + z)/10)^{-3/2} M_\odot$. Cooling by molecular hydrogen may allow even smaller systems to form. Feedback effects are very important in these shallow potential wells – for instance, one supernova could eject many thousand times its own mass, and even photoionization by the first O and B stars could dislodge gas from these shallow potential wells.

The IGM remained predominantly neutral until a sufficient number of ‘subgalaxies’ above this characteristic mass had gone non-linear to provide the requisite O-B stars (or accreting black holes) that photoionized the IGM. How many of these ‘subgalaxies’ formed, and how bright each one would be, depends on another big uncertainty: the IMF for Population III stars. They form in an unmagnetised medium of pure H and He bathed in background radiation which may be hotter than 50 K when the action starts (at redshift $z$ the temperature is of course $2.7(1 + z)$ K). Would these conditions favour a flatter or a steeper IMF than we observed today? This is completely unclear: the density may become so high that fragmentation proceeds to very low masses (despite the higher temperature and absence of coolants other than molecular hydrogen); on the other hand, massive stars may be more favoured than at the present epoch. Indeed, fragmentation could even be so completely inhibited that the first things to form are supermassive holes.
The gravitational aspects of clustering can be computed with convincingly high resolution. So also, now, can the dynamics of the baryonic (gaseous) component – including shocks and radiative cooling. But the huge dynamic range of the star-formation process cannot be followed deductively, so the nature of the simulation changes as soon as the first stars (or other compact objects) form. The first stars exert crucial feedback – the remaining gas is heated by ionizing radiation, and perhaps also by an injection of kinetic energy via winds and even supernova explosions – and this depends on the IMF, and on further uncertain physics.

So three major uncertainties are:

(i) What is the IMF of the first stellar population? The high-mass stars are the ones that provide efficient (and relatively prompt) feedback. It plainly makes a big difference whether these are the dominant type of stars, or whether the initial IMF rises steeply towards low masses (or is bimodal), so that very many faint stars form before there is a significant feedback.

(ii) Quite apart from the uncertainty in the IMF, it is also unclear what fraction of the baryons that fall into a clump would actually be incorporated into stars before being re-ejected. The retained fraction would almost certainly depend on the virial velocity: gas more readily escapes from shallow potential wells.

(iii) The influence of the early stars depends on whether their energy is deposited locally or penetrates into the medium that is not yet in contracting systems. The UV radiation could, for instance, be mainly absorbed in the gas immediately surrounding the first stars, so that it exerts no feedback on the condensation of further clumps – the total number of massive stars or accreting holes needed to build up the UV background, and the possible concomitant contamination by heavy elements, would then be greater.

Perhaps I’m being pessimistic, but I doubt that either observations or theoretical progress will have eliminated these uncertainties about the ‘dark age’ by the time NGST flies. Later speakers at the conference, especially Drs Loeb, Ferrara and Madau, will be addressing some aspects of these issues. I will merely try to highlight some key questions that NGST could address.

3 The Epoch of Ionization Breakthrough

3.1 Why is the breakthrough epoch important?

Quasar spectra tell us that the IGM is almost fully ionized back to $z = 5$, but we do not know when the universe in effect became an HII region. This question must be answered before we can properly interpret angular fluctuations in the CMB radiation. If the intergalactic medium is essentially fully ionized back to a redshift $z_i$, then the scattering opacity scales roughly as $(1 + z_i)^{3/2}$. Even when this optical depth is far below unity, the ionized gas constitutes a ‘fog’ that attenuates the fluctuations imprinted at the re-
combination era; the fraction of photons that are scattered at $< z_i$ then manifest a different pattern of fluctuations, characteristically on larger angular scales. This optical depth is consequently one of the parameters that can in principle be determined from CMB anisotropy measurements. It is feasible to detect a value as small as 0.1 – polarization measurements of the kind expected from Planck-Surveyor may allow even greater precision, since the scattered component would imprint polarization on angular scales of a few degrees, which would be absent from the Sachs Wolfe fluctuations on that angular scale originating at $t_{\text{rec}}$.

The thermal history of the IGM beyond $z = 5$ is relevant to the modelling and interpretation of the absorption spectra of quasars at lower redshifts. The recombination and cooling timescales for diffuse gas are comparable to the cosmological expansion timescale. Therefore the ‘texture’ and temperature of the filamentary structure responsible for the lines in the ‘forest’ carry fossil evidence of the thermal history at higher redshifts.

3.2 Why is $z_i$ so uncertain?

Even if we knew exactly what the initial fluctuations were, and when the first bound systems on each scale formed, the efficiency of UV generation in the IGM depends on OB star formation, possibly on early black hole formation, and also on whether UV photons can escape from the dense gas around their points of origin. These processes are so poorly understood that the breakthrough redshift $z_i$ is uncertain by a factor of 2, even if we postulate a ‘standard’ IMF; once we admit a possibly different IMF, the uncertainty widens still more. This can be easily seen as follows:

Ionization breakthrough requires 1-10 photons for each baryon in the IGM. An OB star produces $10^4 - 10^5$ ionizing photons for each constituent baryon, so the requisite UV could be supplied by $10^{-3}$ of the baryon turning into stars with a standard IMF. We can then contrast two cases:

(A). If the star formation were efficient, in the sense that all the baryons that ‘went non-linear’, and fell into a CDM clump larger than the Jeans mass, turned into stars, then only the rare 3-$\sigma$ peaks in the initial fluctuation spectrum would suffice. On the other hand:

(B). Star formation could plausibly be so inefficient that less than 1 percent of the baryons in these pregalactic systems condense into stars, the others being expelled by stellar winds, supernovae, etc., In this case, production of the necessary UV would have to await the collapse of more typical peaks (1.5-$\sigma$, for instance).

A 1.5-$\sigma$ peak has an initial amplitude only half that of a 3-$\sigma$ peak, and would therefore collapse at a value of $(1 + z)$ that was lower by a factor of 2. For plausible values of the fluctuation amplitude this would change $z_i$ from 15 (scenario A) to 7 (scenario B). There are of course other complications, stemming from the possibility that many of the UV photons may be reabsorbed locally; moreover in Scenario B the formation of sufficient OB stars might have to await the build-up of
larger systems in which stars would form more efficiently.

If the IMF were biased towards low-mass stars, the situation resembles inefficient star formation with respect to ionization. However, there is the possibility that, before enough UV as been generated, a substantial fraction of the baryons could be condensed into low mass stars. This population could be sufficient to contribute to the MACHO lensing events (see section 5).

Note that scenarios A and B would have interestingly different implications for the formation and dispersal of the first heavy elements. If B were correct, there would be a large number of locations whence heavy elements could spread into the surrounding medium; on the other hand, scenario A would lead to a smaller number of more widely spaced sources.

3.3 AGNs at high $z$?

By the epoch $z = 5$, some structures (albeit perhaps only exceptional ones) must have attained galactic scales. Massive black holes (manifested as quasars) accumulate in the deep potential wells of these larger systems. Quasars may dominate the UV background at $z < 3$: if their spectra follow a power-law, rather than the typical thermal spectrum of OB stars, then quasars are crucial for the second ionization of He. AGN formation may require virialised systems with large masses and deep potential wells (cf Haehnelt and Rees 1993); if so, we would naturally expect the UV background at the highest redshifts to be contributed mainly by stars in ‘sub-galaxies’. However, this is merely an expectation; it could be, contrariwise, that black holes readily form even in the first $10^8 M_\odot$ CDM condensations (this would be an extreme version of a ‘flattened’ IMF). Were this the case, the early UV production could be dominated by black holes. This would imply that the most promising high-$z$ sources to seek with NGST would be miniquasars, rather than ‘subgalaxies’. It would also, of course, weaken the connection between the ionizing background and the origin of the first heavy elements.

3.4 Detectability of ‘pregalactic’ UV sources and determination of $z_i$

The detectability of these early-forming systems, of subgalactic mass, depends on whether (A) or (B) (section 3.2) is nearer the truth. This is discussed in a recent paper by Jordi Miralda Escudé and myself (1998). There are already some constraints from the Hubble Deep Field, particularly on the number of ‘miniquasars’ (Haiman, Loeb and Madau 1998). Objects down to AB mag of 31 could be detected from the ground by looking at a field behind a cluster where there might be gravitational-lens magnification; but firm evidence is likely to await NGST.

3.5 Distinguishing between objects with $z > z_i$ and $z < z_i$

The blanketing effect due to the Lyman alpha forest – known to be becoming denser
towards higher redshifts, and likely therefore to be even thicker beyond \( z = 5 \) – would be severe, and would block out the blue wing of Lyman alpha emission from a high-\( z \) source. Such objects may still be best detected via their Lyman alpha emission even though the absorption cuts the equivalent width by half. But at redshifts larger than \( z_i \) – in other words, before ionization breakthrough – the Gunn-Peterson optical depth is so large that any Lyman alpha emission line is blanketed completely, because the damping wing due to IGM absorption spills over into the red wing (Miralda Escudé 1998). This means that any objects detectable beyond \( z \) would be found by a discontinuity at the redshifted Lyman alpha frequency. The Lyman alpha emission line itself would not be detectable (even though this may be the easiest feature to detect in objects with \( z < z_i \)).

4 Detecting Very Distant Supernovae with NGST

It is straightforward to calculate how many supernovae would have gone off, in each comoving volume, as a direct consequence of this output of UV and heavy elements if the reheating and ionization were due to OB stars (cf Haiman and Loeb 1997, Gnedin and Ostriker 1997, Songalia 1997, Cowie 1998): there would be one, or maybe several, per year in each square arc minute of sky (Miralda-Escudé and Rees 1997). The uncertainty depends partly on the redshift and the cosmological model, but also on the uncertainties about the UV background, and about the actual production of heavy elements. (These may be overestimated because the heavy element distribution is ‘patchy’, and concentrated in the overdense regions that yield high-column density absorption features. On the other hand, they may be underestimated if most are concentrated in the sources; moreover, if most of the UV is absorbed near its source, then more production is needed to generate the required intergalactic ionization.)

These high-\( z \) supernovae would be primarily of Type 2. The typical observed light curve has a flat maximum lasting 80 days. One would therefore (taking the time dilation into account) expect each supernova to be near its maximum for nearly a year. It is possible that the explosions proceed differently when the stellar envelope is essentially metal-free, yielding different light curves, so any estimates of detectability are tentative. However, taking a standard Type 2 light curve (which may of course be pessimistic), one calculates that these objects should be approx 27th magnitude in J and K bands even out beyond \( z = 5 \). The detection of such objects would be an easy task with the NGST. With existing facilities it is marginal. The best hope would be that observations of clusters of galaxies might serendipitously detect a magnified gravitationally-lensed image from far behind a cluster.

The first supernovae could be important for another reason: they may generate the first cosmic magnetic fields. Mass loss (via winds or supernovae permeated
by magnetic flux) would disperse magnetic flux along with the heavy elements. This flux, stretched and sheared by bulk motions, can be the ‘seed’ for the later amplification processes that generate the larger-scale fields pervading disc galaxies.

(Incidentally, it is now clear that the afterglows of gamma-ray bursts are 100 times brighter than supernovae. The rate, however, is low – even though it could exceed that of the bursts themselves if the gamma rays are more narrowly beamed than the slower-moving ejecta that cause the afterglow. Detection of an afterglow beyond $z = 5$ would offer a marvellous opportunity to obtain a high-resolution spectrum of intervening absorption features.)

5 Where are the Oldest Stars?

The efficiency of early mixing is important for the interpretation of stars in our own galaxy that have ultra-low metallicity – lower than the mean metallicity that would have been generated in association with the UV background at $z > 5$ (cf Norris 1994). If the heavy elements were efficiently mixed, then these stars would themselves need to have formed before galaxies were assembled. To a first approximation they would cluster non-dissipatively; they would therefore be distributed in halos (including the halo of our own Galaxy) like the dark matter itself. More careful estimates slightly weaken this inference, This is because the subgalaxies would tend, during the subsequent mergers, to sink via dynamical friction towards the centres of the merged systems. There would nevertheless be a tendency for the most extreme metal-poor stars to have a more extended distribution in our Galactic Halo, and to have a bigger spread of motions. This is another project where NGST could be crucial, especially if it allowed detection of halo stars in other nearby galaxies.

The number of such stars depends on the IMF. If this were flatter, there would be fewer low-mass stars formed concurrently with those that produced the UV background. If, on the other hand, the IMF were initially steeper, there could in principle be a lot of very low mass (macho) objects produced at high redshift, many of which would end up in the halos of galaxies like our own.

6 Summary

Perhaps only 5 per cent of star formation occurred before $z = 5$. But at the conference on NGST held last year at Goddard Space Flight Center, Alan Dressler, in his concluding lecture, rightly emphasised that these early stars were important, just as were the first 5 percent of humans. There is still a variety of models for cosmic structure, that seem consistent with the properties of our universe at the current epoch. Large-scale structure may be elucidated within the next decade, by ambitious surveys (2-degree field and Sloan) and studies of CMB anisotropies. But there will still be uncertainty about
how the present structures emerged, and especially about the efficiency and modes of star formation in early structures on subgalactic scale.

NGST will have many roles. But in deciding the tradeoffs between aperture, waveband coverage, and image quality, it is important to optimise this unique chance to elucidate the formative stages of cosmic structure.

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