The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
Proceedings IAU Symposium No. 308, 2014
R. van de Weygaert, S. Shandarin, E. Saar & J. Einasto, eds.

doi:10.1017/S1743921316010474

The Direct Collapse of Supermassive Black Hole Seeds

John A. Regan[1], **Peter H. Johansson**[1] **and John H. Wise**[2]

[1]Department of Physics, University of Helsinki, Finland
email: `john.regan@helsinki.fi`

[2]Center for Relativistic Astrophysics, Georgia Institute of Technology, USA

Abstract. The direct collapse model of supermassive black hole seed formation requires that the gas cools predominantly via atomic hydrogen. To this end we simulate the effect of an *anisotropic* radiation source on the collapse of a halo at high redshift. The radiation source is placed at a distance of 3 kpc (physical) from the collapsing object and is set to emit monochromatically in the center of the Lyman-Werner (LW) band. The LW radiation emitted from the high redshift source is followed self-consistently using ray tracing techniques. Due to self-shielding, a small amount of H_2 is able to form at the very center of the collapsing halo even under very strong LW radiation. Furthermore, we find that a radiation source, emitting $> 10^{54}$ ($\sim 10^3$ J_{21}) photons per second is required to cause the collapse of a clump of $M \sim 10^5$ $M_\odot$. The resulting accretion rate onto the collapsing object is ~ 0.25 $M_\odot$ yr^{-1}. Our results display significant differences, compared to the isotropic radiation field case, in terms of H_2 fraction at an equivalent radius. These differences will significantly effect the dynamics of the collapse. With the inclusion of a strong anisotropic radiation source, the final mass of the collapsing object is found to be $M \sim 10^5$ $M_\odot$. This is consistent with predictions for the formation of a supermassive star or quasi-star leading to a supermassive black hole.

Keywords. Cosmology: theory – large-scale structure – black holes physics – methods: numerical – radiative transfer

1. Introduction

The discovery of Super Massive Black Holes (SMBHs) (e.g. Mortlock *et al.* 2011) at very high redshift ($z > 6$) has led to a difficulty in explaining how black hole seeds formed so early in the Universe. The seed (progenitor for the SMBH) must grow from its initial mass early in the Universe to a mass $M \gtrsim 10^9 M_\odot$ by a redshift of $z \sim 6$. The direct collapse model of SMBH growth provides a compelling solution. In this model a collapsing baryonic mass, which can cool only through Lyman-α radiation, provides an initial seed mass black hole of $M_{BH} \sim 10^4$ $M_\odot$ (e.g. Regan & Haehnelt. 2009a, Regan *et al.* 2014a). In order for the collapsing gas cloud to cool only through atomic transitions H_2 must be effectively dissociated and the cloud must be deficient in metals. H_2 readily forms in the early Universe and so in order for the halo to cool through atomic transitions only H_2 must be dissociation by a radiative background or else collisionally dissociated though collisions with other primordial elements. The assumption of very low metallicity within the halo is easily satisfied at high redshifts due to the limited time for metals to pollute all collapsing halos.

2. Anisotropic Radiation Sources

In order to dissociate H_2, radiation in the Lyman-Werner (LW) bands is required. The LW band occupies the frequency spectrum between $\sim 11.2 \; - -13.6$ eV. Furthermore, the global LW background at high-z is likely to be relatively low and so a close-by, high

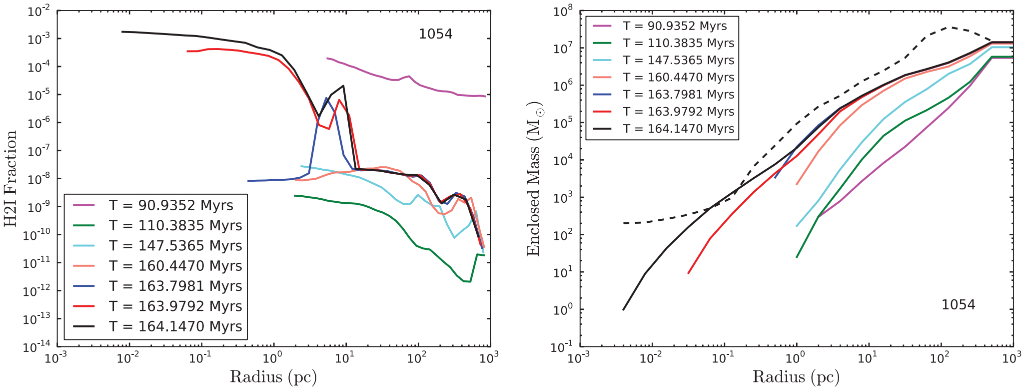

Figure 1. In both panels we show a radial profile centred on the point of maximum density in the simulation i.e. centred on the collapsing halo. In both cases the source is exposed to a radiation source emitting 10^{54} photons per second in the Lyman-Werner band corresponding to $\sim 10^3$ J_{21}. In the left hand panel we show the H_2 fraction and in the right hand panel we show the enclosed mass. The dashed line in the right hand panel is the Jeans mass at the last output time.

intensity, LW flux will be required to reach sufficient intensities (e.g. Dijkstra *et al.* 2008). This anisotropic source will be able to effectively dissociate H_2 as long as it is within ~ 10 kpc and has a flux of $\gtrsim 10^3$ J_{21}, where $J_{21} = 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}.

3. Simulations & Results

To model the direct collapse of SMBH seeds at high redshift we use hydrodynamical simulations including self-consistent radiative transfer to study the collapse. We use the publicly available `Enzo` code (Byran *et al.* 2014). We simulate a single halo using a series of fluxes from a source located at a distance of 3 kpc (physical)(Regan *et al.* 2014b). In Figure 1 we show the results from the simulation with a source flux of 1×10^{54} photons per second for clarity ($\sim 10^3 J_{21}$). We found that this was close to the minimum flux required in order that H_2 self-shielding would be overcome.

4. Conclusions

A flux in the LW band of J $\sim$ a few times J_{21} delays the collapse of the gas cloud by up to 70 Myrs as the cooling due to H_2 is inhibited. Fluxes in the LW band of J $\gtrsim 10^3 J_{21}$ cause the formation of a collapsing cloud of M $\sim 10^5$ $M_\odot$ suggesting a SMBH seed of this mass will form if fragmentation can be prevented.

Furthermore, our simulations suggest that an anisotropic source is required and will significantly effect the dynamics of the collapse compared to the isotropic radiation case. Otherwise identical simulations run with isotropic radiation and anisotropic radiation showed differences of up to two orders of magnitude in the H_2 abundances at a given radius which will strongly effect the collapse.

References

G. L. Bryan and The Enzo Collaboration. *AstroPhysical Journal*, 211:19, April 2014.
M. Dijkstra *et al. Monthly Notices*, 391:1961–1972, December 2008.
D. J. Mortlock *et al. Nature*, 474:616–619, June 2011.
J. A. Regan & M. G. Haehnelt. *Monthly Notices*, 393:858–871, March 2009.
J. A. Regan & M. G. Haehnelt. *Monthly Notices*, 396:343–353, June 2009.
J. A. Regan *et al. Monthly Notices*, 439:1160–1175, March 2014.
J. A. Regan, P. H. Johansson, & J. H. Wise. *ArXiv e-prints:1407.4472*, July 2014.