High-z objects and cold-dark-matter cosmogonies: the case of 53W091.

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Abstract: The recently discovered high redshift galaxy, 53W091, with accurate age measurements (Dunlop et al 1996) provides a measure of the small-scale power of the primordial density field and, as we show, a crucial test of the inflation-inspired models. It allows $\Omega=1$ cosmologies only for low values of H_0 , but then pushes formation of that galaxy to redshift much greater than allowed for by the cold-dark-matter density field. Cold-dark-matter (CDM) models with cosmological constant (Λ) and low Ω would decrease the redshift at which this galaxy has collapsed. However, in CDM models decreasing Ω suppresses the small scale power in the density field and this effect turns out to be dominant. We estimate the mass of the galaxy and show that it represents a very rare and unlikely event in the density field of such models. Similar problems would occur in other modifications of the CDM cosmogonies.

1. Introduction

Inflation provides an attractive framework to explain the origin of the large scale structure in the Universe. At the same time it makes two firm predictions: 1) if started from inhomogeneous initial conditions and later homogeneised by inflationary expansion, the Universe must be flat today to be consistent with the microwave background anisotropy measurements (Kashlinsky, Tkachev & Frieman 1994); and 2) the primordial power spectrum of the density field is of the Harrison-Zeldovich form modified only by a different growth rate for sub- and super- horizon fluctuations during the radiation dominated era (e.g. Bardeen et al 1986).

The epoch of galaxy formation reflects the small scale power in the primordial density field as well as cosmological parameters and thus provides an additional test of cosmological theories.

We show that the high-z galaxy, 53W091, recently discovered by Dunlop et al (1996; D96), provides a sensitive test of inflationary models (Kashlinsky & Jimenez 1996). The age of the galaxy estimated from its red stellar population formally rules out Einstein-de Sitter for $H_0 > 50 \,\mathrm{km/sec/Mpc}$. For smaller values

of H_0 the redshift of formation of the galaxy is so high that 53W091 will have to be a >10- σ event for the density field predicted by standard inflationary paradigm. To reconcile such old and as we show below massive galaxy with inflationary paradigm requiring flat Universe, the alternative may seem at first to assume a cosmological constant, $\Lambda \equiv 3H_0^2\lambda$, dominated Universe with $\Omega + \lambda = 1$. Inter alia this model was proposed to account for the excess large-scale power seen in galaxy catalogs within the inflationary picture (Efstathiou et al 1990). This would also allow more time for the galaxy to evolve and push its formation to lower z. However, increasing the cosmological constant, λ , and decreasing Ω would at the same time suppress the small scale power in the density field and push galaxy collapse and formation to more recent epochs. We show that the latter makes 53W091 a >(6-7)- σ event in such models. Consequently the galaxy represents a challenge to all inflation inspired cosmogonies.

2. Parameters of 53W091

The discovery of and data on 53W091 were recently presented in D96. Its red color is indicative of an old stellar population and its blue apparent magnitude V=26 implies a large luminous mass. They have been able to identify late-type stellar absorption features in the spectrum of the galaxy which allow one to determine the age. The spectrum for 53W091 was obtained in the range 2000 to 3500 Å, where the main contribution to the integrated light comes from the main sequence stars. Hence D96 built a series of synthetic spectra at different ages with the main contribution coming from the main sequence stars. This was done using the set of stellar atmospheres models from Kurucz (1992) and a grid of stellar interior models from Jimenez & MacDonald (1997).

The best fit was found for the age of $t_{age}=3.5 \,\mathrm{Gyr}$ (D96). An independent evidence that the age of 53W091 cannot be less than 3 Gyr comes from transition breaks in the spectrum. The two of them, at 2600 and 2900 Å, were computed for different metallicities $(1/5~Z_{\odot},~Z_{\odot},~\mathrm{and}~2~Z_{\odot})$; the observed amplitudes showed that the breaks cannot be reproduced if $t_{age}<3 \,\mathrm{Gyr}$ (D96). The numbers for t_{age} were computed in D96 assuming 53W091 to be an elliptical, i.e. assuming that the α -nuclei elements are enhanced with respect to the Sun with the typical enhancement factors being $[\alpha/\mathrm{Fe}]=0.3$ -0.5. We therefore follow D96 and adopt for the present discussion the age uncertainty of the 53W091 galaxy to be no more than 0.5 Gyr with the most likely value of $t_{age}=3.5 \,\mathrm{Gyr}$. Pushing the age to the lower limit of the range, $t_{age}=3 \,\mathrm{Gyr}$, would at the same time require high metallicity $(Z \geq 2~Z_{\odot})$ typical of nuclei of ellipticals. (The galaxy was observed with an aperture of 4 " making the nucleus region unresolved).

One needs to estimate the mass of 53W091 in order to test its implications for galaxy formation. To compute the total luminous mass of the galaxy we used the integrated synthetic spectra from D96. The flux was then scaled assuming the Miller-Scalo IMF until it matched the observed fluxes in all, V,J,H,K, bands from D96. The effect of changing the slope of the IMF on the total luminous mass is generally small: $\sim 1\%$ when the IMF slope, α , changes from 2.5 to 3.5. We computed the total mass in stars in the galaxy for different cosmologies. For

the case of $\Omega = 1.0, \Lambda = 0, H_0 = 60 \text{ km/sec/Mpc}$, the mass was calculated for 3 different metallicities (1/5, 1 and 2 Z_{\odot}). We found a value for the mass of 53W091 between 0.8×10^{12} and $1.3 \times 10^{12} M_{\odot}$. Subsequently, we studied models with solar metallicity and $\Lambda = 0, H_0 = 60 \text{ km/sec/Mpc}$ but for different values of Ω (0.2, 0.3, 0.4). In this case the computed mass was found between 1.1×10^{12} and $1.9 \times 10^{12} M_{\odot}$. Finally, we computed the mass for different values of H_0 with $\Omega = 1$ and solar metallicity. The mass values are in between 1.1×10^{12} and $2.4 \times 10^{12} M_{\odot}$ (see Kashlinsky & Jimenez (1996) for more details). Because of the increasing distances, for flat $\Omega + \lambda = 1$ models the mass is even higher. E.g. for the flat Λ -dominated Universe with Ω =0.2 the total stellar mass for 53W091 is $1.8 \times 10^{12} M_{\odot}$. The trends with H_0 and Ω are very similar to the $\Lambda=0$ case; for brevity we do not present the numbers here. In order to account for different rates of star formation we adopted the star formation prescription described in Chambers & Charlot (1990) and computed a series of integrated synthetic spectra with different values for the typical star formation rate parameter τ . The change in the total star mass for different star formation laws is small, particularly in the likely case of τ <2Gyr. Larger τ lead to $Z\gg Z_{\odot}$ and also give larger M: e.g. if $\tau \ge 3$ Gyr, the mass estimates shown in Table 1 increase by 37%. The numbers vary little with model or cosmological parameters and show that 53W091 has $\geq 10^{12} M_{\odot}$ in stars alone inside the aperture of 4".

3. Cosmology

Following the results from the previous section we assume in what follows that the data on 53W091 imply that the galaxy at z=1.55 has mass in excess of $10^{12} M_{\odot}$ and its stellar population has age of $\simeq 3.5$ Gyr. What are then the cosmological implications of at least one object in the Universe having collapsed (formed galaxy) on mass scale of $> 10^{12} M_{\odot}$ at least 3.5 Gyr before the redshift of 1.55?

The left box in Fig.1 shows the redshift z_{gal} at which the galaxy 53W091 must have formed its first stars for $\Omega+\lambda=1$ Universe. Solid lines correspond to $t_{age}=3$ Gyr, dotted to 3.5 Gyr and dashed to 4 Gyr. Three types of each line correspond to $H_0=60,80$ and 100 km/sec/Mpc. One can see that the value of z_{gal} decreases as both Ω and h decrease. On the other hand, in the low- Ω CDM cosmogonies the small-scale power is also reduced as the product Ωh decreases; this would at the same time delay collapse of first galaxies until progressively smaller z.

To quantify this we proceed in the manner outlined in Kashlinsky (1993). This involves the following steps (see Kashlinsky & Jimenez 1996 for details): 1) Specify the primordial power spectrum, P(k), of the density field at some initial redshift $z_i \gg 1$ when the density field is linear on all scales. The power spectrum depends on the initial power spectrum, assumed to be Harrison-Zeldovich, and the transfer function which accounts for the evolution of the shape of the power spectrum in the linear regime. The latter depends in such models only on the product Ωh and was adopted from Bardeen et al (1986). 2) Compute the amplitude, Δ_8 , of that field at z_i on the scale of $8h^{-1}$ Mpc that produces the

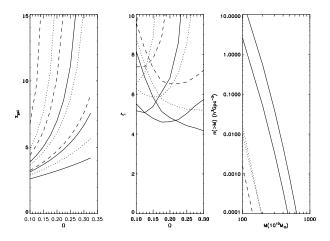


Figure 1.

observed unity rms fluctuation in galaxy counts today, or a 1/b amplitude in mass fluctuation (b is the bias factor) at z=0; 3) Compute the density, $\delta_{col}(z)$, the fluctuation had to have at z_i in order to collapse at z. 4) A convenient quantity to describe 2) and 3) is $Q(z) \equiv \delta_{col}(z)/\Delta_8$. For Λ -dominated flat Universe and in the limit of $1+z_{gal} > \Omega^{-1/3}$ it can be approximated as $Q(z) \simeq 3\Omega^{0.225}b^{2/3}(1+z)$. 5) b is determined by normalizing the density distribution given by P(k) to the COBE-DMR maps (Bennett et al 1994; Stompor et al 1995). 6) Given P(k) we compute the rms fluctuation, $\Delta(M)$, over a region containing mass M. 7) The quantity $\zeta \equiv Q(z_{gal})\Delta_8/\Delta(M)$ then describes the number of standard deviations an object of mass M had to be in order to collapse at z_{gal} in the cosmological model specified by P(k).

The values of ζ for $M=10^{12}M_{\odot}$ are plotted versus Ω in the middle box of Fig.1 for $\Omega+\lambda=1$ for various values of t_{age} and h. As in the left box solid lines correspond to $t_{age}=3$ Gyr, dotted to 3.5 and dashes to 4 Gyr. Three types of each line correspond to h=0.6, 0.8 and 1 going from bottom to top at large values of Ω at the right end of the graph. The line for $t_{age}=4$ Gyr and h=1 lies above the box. As the figure shows, this galaxy must represent an extremely rare fluctuation in the density field specified by the low- Ω flat CDM models. Note that the total mass of 53W091 must be at least a factor of 10 larger in which our conclusion will be much stronger.

The right box shows the expected co-moving number density of such galaxies, n(>M), in units of $(h^{-1}\mathrm{Gpc})^{-3}$ vs the total (dark+luminous) mass for $t_{age}=3.5\mathrm{Gyr}$. It was computed using the Press-Schechter (1974) prescription. The numbers for the co-moving number density n(>M) were computed for $\Omega=0.1,0.2,0.3$ and h=1,0.8,0.6. Solid lines correspond to $\Omega=0.1$ and to h=1,0.8 from top to bottom. Dotted lines correspond to $\Omega=0.2$ and h=0.8,0.6 from top to bottom respectively. The dashed line corresponds to $\Omega=0.3$ and h=0.6. The models not shown lie below the box.

4. Conclusions

We have shown that within the framework of the standard and Λ -dominated CDM models objects like 53W091 must be extremely rare in the Universe. There exists a narrow range of parameters (total mass of $10^{12} M_{\odot}$, age of < 3 Gyr, Ω =0.1 and $h \geq 0.8$) where one expects to find a few of such objects with each horizon, $R_{hor} \simeq 6h^{-1}{\rm Gpc}$ for Ω =1, but for most cases the number density of such objects is less than one per horizon volume. The data suggest that the Universe contains more collapsed galaxies at early times than the modified CDM models would predict. Such objects can be most readily accommodated by assuming both 1) low Ω Universe and 2) the small-scale power in the primordial power spectrum in excess of that given by simple inflationary models. E.g. the necessarily high redshift of galaxy formation can be produced in string models (Mahonen, Hara & Miyoshi 1995) or in the phenomenological primeval baryon isocurvature model (Peebles 1987).

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QUESTION: Josh Barnes: Could this galaxy be lensed and thus have amplified flux?

ANSWER: In principle yes, but this is not very likely. A way out for CDM models could be to assume that the stars in 53W091 galaxy formed in smaller collapsed objects and later merged into the galaxy as we see it. However, this too appears unlikely. 53W091 looks like a normal old relaxed giant elliptical. The physical diameter size corresponding to the aperture of 4" at z=1.55 is 29, 20 and 17 h^{-1} Kpc for $(\Omega, \lambda)=(0.1,0.9),(0.1,0)$ and (1,0) respectively; this is typical of diameters of giant ellipticals. It would be hard to see how mergers could have led to the substructure dissipating its energy to collapse to what appears a normal elliptical radius in such a short time. The galaxy has very red colors, indicating no star formation for the past 3Gyr, so this would further have to occur without significant star formation expected from merger events. Indeed, if the galaxy had undergone mergers 3.5 Gyr ago, the following star formation events would have created a significant blue component in its spectrum contrary to what is observed. Thus it is likely that for at least 3.5 Gyr 53W091 did not undergo any major merging events and its mass 3.5 Gyr ago had to be the same. Even invoking mergers would not help much. At the relevant masses and the CDM power spectra $\zeta \propto M^{0.1-0.15}$ for the relevant cosmological parameters, so in order to decrease ζ appreciably 53W091 must have undergone a very large number of mergers in a short time. The $\zeta - M$ dependence would also mean that even if lensing could have led us to overestimate its true luminosity and mass, this would not help much in trying to account for 53W091 in the framework of CDM models.

QUESTION: Ben Dorman: This is a cautionary note about drawing inferences from 2600/2900 Åbreak indices based on the Kurucz fluxes. These model spectra may not reproduce the spectra of the real stars well enough to be sure of the results. There are not yet enough empirical spectra in the wavelength range to check the calculations. It is true, however, that the continuum level observed implies, for a wide range in metallicity, an age of ~ 3 Gyrs, but there is still room for a younger interpretation if Z is > 2 solar. (Though one might argue that luminosity weighted mean abundances much higher than this are unlikely).

ANSWER: It is true that Kurucz models are mostly theoretical. Nevertheless, there are several points that support the Dunlop et al age values for 53W091: 1) An age of ~ 3 Gyr was also obtained using the Bruzual and Charlot code which is based on the IUE observed spectra. Analyzing the breaks values for single stars from the IUE atlas shows that there are stars with breaks values like those of 53W091 and some with higher values. The stars with breaks similar to 53W091 are F6 class with an age of ~ 3.5 Gyr. 2) The breaks are NOT so sensitive to metallicity (see Dunlop et al 1996, Nature 381, 581). As mentioned in the question the mean metallicities of comparably massive giant ellipticals at low redshift are at most only mildly super-solar when averaged out to the extension of the galaxy. 3) The 2600/2900 Åbreaks from

Kurucz models give a good fit to the age of the Sun. In case these breaks were modified (decreasing them to produce a younger age for 53W091) they would yield a MS turnoff age of <3 Gyr for the Sun.