FERMILAB-PUB-07-544-A

DRAFT VERSION FEBRUARY 2, 2008
Preprint typeset using LaTeX style emulateapj v. 10/09/06

ARE THERE ENOUGH IONIZING PHOTONS TO REIONIZE THE UNIVERSE BY $Z \approx 6$?

NICKOLAY Y. GNEDIN[1,2,3]

Draft version February 2, 2008

ABSTRACT

An estimate for the number of ionizing photons per baryon as a function of redshift is computed based on the plausible extrapolation of the observed galaxy UV luminosity function and the latest results on the properties of the escape fraction of ionizing radiation. It is found that, if the escape fraction for low mass galaxies ($M_{\rm TOT} \lesssim 10^{11} M_{\odot}$) is assumed to be negligibly small, as indicated by numerical simulations, then there are not enough ionizing photons to reionize the universe by $z = 6$ for the cosmology favored by the WMAP 3rd year results, while the WMAP 1st year cosmology is marginally consistent with the reionization requirement. The escape fraction as a function of galaxy mass would have to be constant to within a factor of two for the whole mass range of galaxies for reionization to be possible within the WMAP 3rd year cosmology.

Subject headings: cosmology: theory - cosmology: large-scale structure of universe - galaxies: formation - galaxies: intergalactic medium

1. INTRODUCTION

Studies of cosmic reionization - especially theoretical ones - have never been considered as a “photon-starved” field. Theorists always felt free to adjust the emissivity of the ionizing sources, usually quantified by the escape fraction of ionizing radiation, to adjust the reionization redshift to their choosing.

This approach was, indeed, justified in the earlier studies, since until recently limited knowledge existed on the reasonable values for the escape fraction at high redshifts. However, the latest observational (Giallongo et al. 2002; Fernández-Soto et al. 2003; Shapley et al. 2006; Chen et al. 2007) and numerical (Razoumov & Sommer-Larsen 2006, 2007; Gnedin et al. 2007) studies finally begin to converge on the values and evolution of the escape fraction of ionizing radiation and on the relative escape fraction between the far UV and Lyman limit. Three properties of the escape fraction are particularly important for reionization studies: (1) the value of escape fraction is small (a few percent at most), which is an order of magnitude smaller than is assumed in some reionization modeling, (2) it is weakly dependent on the galaxy mass or star formation rate for large galaxies, and (3) it drops prodigiously for dwarf galaxies. The first two properties are reproduced in all recent studies, both observational and theoretical, and, therefore, are rather robust. The last feature of the escape fraction has only been seen in simulations of Gnedin et al. (2007) and is indicated by measurements of Fernández-Soto et al. (2003)[4], because other simulations and observational studies do not yet have either numerical resolution or sensitivity to resolve dwarf galaxies.

Another important observational advance that places the study of reionization on a much more quantitative footing is the observational determination of the galaxy UV luminosity function down to well below L_* at $z \gtrsim 6$. Since it is not possible to give a comprehensive review of all observations in this *Letter* due to space limitations, I refer the reader to the recent work by Bouwens et al. (2007), who give a detailed review of the current status of existing observational data. While the data for the galaxy luminosity function during the reionization era ($z > 6$) are still sparse, the plausible extrapolation of the observed $z \approx 6$ luminosity functions to higher redshifts can be used to predict the global production of the ionizing radiation to at least within a factor of 2 to 3, i.e. more than an order of magnitude improvement over the previous, purely theoretical, assumptions.

Of course, the most accurate models are only possible with the large-box and high-resolution cosmological simulations, which model in detail the emission of ionizing photons in high redshift galaxies and quasars, the propagation of ionizing radiation in the expanding universe, and absorption of that radiation at cosmic ionization fronts and Lyman limit systems. But even the simplest balance of the available ionizing photons and the number of atoms that need to be ionized before the end of reionization at $z \approx 6$ - as required by the observed transmitted flux in the spectra of high redshift quasars discovered by the SDSS collaboration (Fan et al. 2006) - is a useful exercise after the recent improvements in our understanding of the sources of reionization.

This is the subject of this *Letter*.

2. RESULTS

In order to compute the total number of ionizing photons available for reionizing the universe at any given redshift, the observed luminosity functions need to be extrapolated to earlier redshifts. Such extrapolation is, of course, not unique. However, since the mass function of dark mater halos can be computed sufficiently precisely in a given cosmology at any redshift, the extrapolation of the luminosity function to $z > 6$ can be made reliably if the relationship between the galaxy luminosity and the mass of its dark matter halo can be established.

While such a relationship is unlikely to be a simple function, models that assume a one-to-one correspondence between the galaxy luminosity and the halo mass provide remarkably good fit to a variety of observational tests (Conroy et al. 2006). Thus, as a simple and crude approximation, it is instructive to assume such a relationship between the galaxy UV luminosity L_{UV} for the high redshift galaxies as well.

[1] Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA; gnedin@fnal.gov
[2] Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL 60637, USA
[3] Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637 USA

[4] However, the characteristic galaxy masses below which the escape fraction drops down are somewhat different between those two studies.

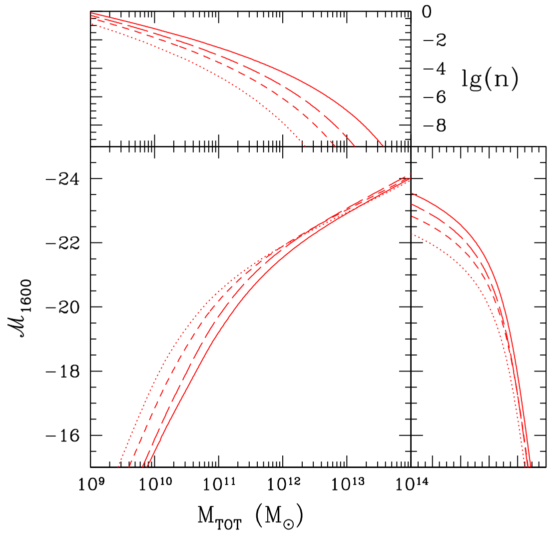

FIG. 1.— The cumulative mass function of dark matter halos (top panel), the cumulative UV luminosity function of galaxies (right panel), and the relationship between the UV absolute magnitude and the halo mass (central panel) obtained by matching the two. Four different lines correspond to $z = 3.8$ (solid lines), $z = 5.0$ (long-dashed lines), $z = 5.9$ (short-dashed lines) and $z = 7.4$ (dotted lines). The observational data are represented by their respective Schechter function fits from Bouwens et al. (2007).

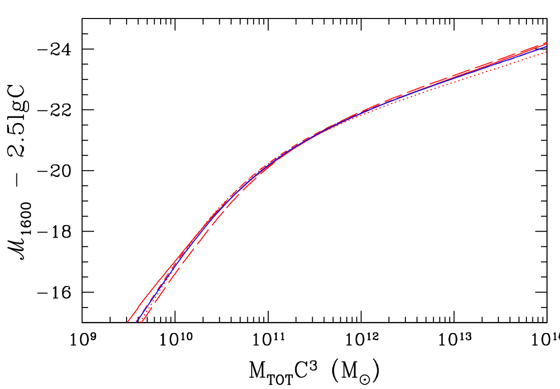

FIG. 2.— The relationship between the UV absolute magnitude and the halo mass from Fig. 1, shifted horizontally and vertically using the correction factor $C = (1+z)/7$ (line styles are as in Fig. 1). Notice that the shift results in a good agreement between different redshifts for all galaxies more massive than about $3\times10^{10}\,M_\odot$. The blue/black solid line marks the average mass-to-light relationship used in the rest of this paper.

In a given cosmology, this relationship between the total mass of a dark matter halo $M_{\rm TOT}$ and the luminosity of a galaxy hosted in that halo $L_{\rm UV}$ can be obtained by matching the cumulative mass and luminosity functions,

$$n(>L_{\rm UV}) = n(>M_{\rm TOT}), \qquad (1)$$

as is shown in Figure 1 for the 4 values of redshift for which Bouwens et al. (2007) give the parameters of the Schechter function fits, assuming the best-fit cosmology for the combination of WMAP 3rd year data and Large Red Galaxies part of SDSS survey (WMAP3; Spergel et al. 2006)[5]. Unfortunately, the derived relation between the UV luminosity (as expressed by the AB absolute magnitude at 1600, $\mathcal{M}_{1600}$) and the total halo mass is redshift-dependent, and so cannot be easily extrapolated to higher redshifts. However, a simple correction of the UV luminosity by a factor of C and the total mass by a factor of C^3 with

$$C(z) = \frac{1+z}{7}$$

eliminates most of the redshift dependence for halos more massive than about $3\times10^{10}\,M_\odot$, as is shown in Figure 2. As I discuss below, these low mass halos contribute almost nothing to the ionizing photon budget, and are so unimportant for the purpose of this paper. Throughout the rest of this paper, I use the average relation marked by a blue/black line in Fig. 2.

The relation between the UV and ionizing luminosities is quantified by the *relative* escape fraction, $f_{\rm esc,rel} = f_{\rm esc}(912)/f_{\rm esc}(1600)$ and the value of the intrinsic ratio of stellar luminosities at these two wavelength, $r_{\rm int} = (L_{1600}/L_{912})_{\rm int}$. For the escape fraction at the Lyman limit I adopt the results of Gnedin et al. (2007), who found that in high resolution simulation of galaxies with radiative transfer escape fractions for larger galaxies are of the order of a few percent, consistent with observational determinations, but little (if any) radiation escapes from small galaxies. Thus, for the relative escape fraction as a function of galaxy mass I adopt the following form:

$$f_{\rm esc,rel}(M) \approx 0.15 \begin{cases} 1 & \text{if } M_{\rm TOT} > 5\times10^{10}\,M_\odot, \\ s_{\rm min} & \text{otherwise.} \end{cases}$$

This form is consistent with observational measurements of the relative escape fraction (c.f. Shapley et al. 2006) for massive galaxies. The drop in the escape fraction is also indicated in observations of Fernández-Soto et al. (2003), but the characteristic transition occurs at a factor of 10 higher star formation rate, which would correspond to a higher characteristic mass. The adopted value of $5\times10^{10}\,M_\odot$ therefore likely biases the estimate production of ionizing photons up. Here, as well as in the rest of the paper, all uncertain quantities are chosen so that to insure that my estimate for the total number of ionizing photons is likely to be an overestimate, rather than an underestimate. I return to the uncertainty of the main result in the Discussion section.

In Gnedin et al. (2007) simulations, the relative escape fraction of low mass galaxies ($M_{\rm TOT} < 5\times10^{10}\,M_\odot$) never exceeds about 0.01, and is often much lower, so I adopt $s_{\rm min} = 0.05$ as my fiducial value. I consider the effect of parameter $s_{\rm min}$ in the Discussion section.

Using the mass-to-light matching from Fig. 2, the mass dependence can also be recast as the luminosity dependence.

For the intrinsic break, I adopt a value of (Shapley et al. 2006)

$$r_{\rm int} \approx 3.$$

However, Siana et al. (2007) argue for a larger value for the intrinsic break, $r_{\rm int} \approx 6$, and that larger value is also consistent with Starburst99 spectral synthesis models (Leitherer et al. 1999). Here I again adopt a lower value as a fiducial number so that not to underestimate the total number of ionizing photons.

With the above assumption, the total emission rate density of the ionizing photons at a given redshift z can now be expressed as

$$\dot{n}_\gamma = \int dL_{1600}\,\frac{f_{\rm esc,rel}}{r_{\rm int}}\,\frac{L_{1600}}{\langle E\rangle}\,\frac{dn}{dL_{1600}}, \qquad (2)$$

where $\langle E\rangle$ is the average energy of a photo-ionizing photon (which I take to be 22 eV, consistent with typical spectra of star-bursts (Leitherer et al. 1999)) and dn/dL_{1600} is the comoving UV luminosity function obtained from the halo total

[5] $\Omega_M = 0.27$, $h = 0.71$, $n_S = 0.95$, $\sigma_8 = 0.78$

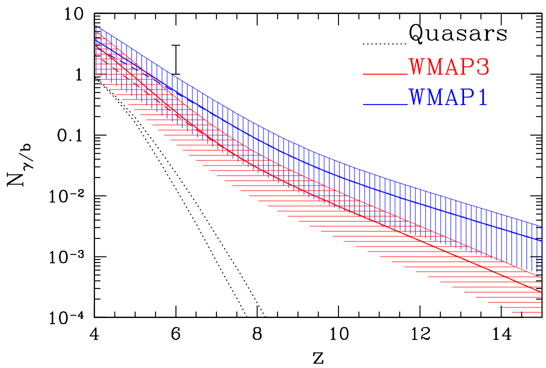

FIG. 3.— The total ionizing photon-to-baryon ratio as a function of redshift for the WMAP3 (red/gray lines) and WMAP1 (blue/black lines) cosmologies. In both cases the dashed lines show the contribution from galaxies only, while solid lines include the quasar contribution (with $s_{\rm min} = 0.05$). The shaded region is an estimate of the upper 95% CL uncertainty (the lower uncertainty is harder to estimate, and so its exact limit is not shown). Two black dotted lines mark the two estimates of the quasar contribution. The adopted reionization criterion, $1 < N_{\gamma/b} < 3$ at $z = 6$, is shown as a segment with error-bars.

mass function using the mass-to-light ratio from Fig. 2. The total number of ionizing photons per baryon at time t is then

$$N_{\gamma/b}(t) = \int_0^t \frac{\dot{n}_\gamma}{n_b} dt,$$

where $n_b \approx 2.5 \times 10^{-7}\,{\rm cm}^{-3}$ is the comoving number density of baryons.

An additional complication in this estimate, however, is introduced by a possible contribution to the ionizing background from high-redshift quasars. Unfortunately, this contribution cannot be estimated with the same method as the contribution from galaxies, because quasars are known to be short-lived, and halos of a given total mass may or may not host a quasar at any given time.

Fortunately, the quasar luminosity function is reasonably well known all the way to $z \approx 5$ (Hopkins et al. 2007). Using the fitting code provided by Hopkins et al. (2007), the emission rate density of ionizing radiation from quasars can be estimated at a range of redshifts $4 < z < 6$. Such an estimate agrees remarkably well with an earlier estimate by Madau et al. (1999): for example, Hopkins et al. (2007) fit at $z = 5$ results in $\log(\dot{n}_\gamma) \approx 50.5$, while Madau et al. (1999) estimate at that redshift is $\log(\dot{n}_\gamma) \approx 50.6$. At $z = 4$ both estimates give the same value of $\log(\dot{n}_\gamma) \approx 50.8$.

The extrapolation of the Hopkins et al. (2007) luminosity function to $z > 5$ is, of course, highly uncertain. In order to approximately account for possible uncertainties, I consider two different extrapolations: the "lower" one simply uses the Hopkins et al. (2007) best-fit model to compute the quasar luminosity function at any redshift; the "higher" extrapolation multiplies the "lower" one by a factor of $[(1+z)/6]^3$ (chosen somewhat arbitrarily), greatly increasing quasar abundance at higher redshifts.

The resultant photon-to-baryon ratio is shown in Figure 3 for two adopted sets of cosmological parameters: the WMAP3 cosmology introduced above and the best-fit values for the pure ΛCDM model from the first year WMAP data (WMAP1; Spergel et al. 2003)[6]. As can be seen, the quasar contribution is smaller than the one from galaxies by at least an order of magnitude, and so its large uncertainty is not that important.

The uncertainty on the estimates from Fig. 3 is not easy to evaluate. The observational 2σ limit on the adopted value of $f_{\rm esc,rel} \approx 0.15$ is about 50% (Shapley et al. 2006; Chen et al. 2007). In addition, the model for the evolution of the ionizing luminosity from galaxies presented above is only approximate. Since the observed luminosity functions are only used to compute the total number of ionizing photons (an integral quantity), the observational 2σ error from the uncertainty in the luminosity functions is about 40% (Bouwens et al. 2007). I increase it to 50% because additional interpolation is involved, and adding the two uncertainties in quadrature, obtain about 70% uncertainty in the upper direction. The lower uncertainty is much larger, since the selected values for all relevant factors are consistently biased toward a larger value of $N_{\gamma/b}$. For example, the value for the intrinsic break $r_{\rm int}$ may be close to 6 than to 3, resulting in additional factor of 2 uncertainty in the downward direction. The lower shaded regions in Fig. 3 include this factor-of-2 uncertainty, but the lower bound of the uncertainty is likely to be even lower, so it is not shown in Fig. 3.

Thus, it is unlikely that curves in Fig. 3 *underestimate* the correct value by more than a factor of two, although they can present a substantial overestimate of the correct result.

3. DISCUSSION

But what is the reionization criterion in terms of $N_{\gamma/b}$? Obviously, the whole process of reionization cannot be supplanted by a single value for $N_{\gamma/b}$. On the other hand, having $N_{\gamma/b} \gtrsim 0.9$ is a *necessary condition* for reionization (assuming that helium is singly ionized and the mass fraction of the neutral hydrogen at $z \approx 6$ is small, consistent with the expected abundance of Lyman limit systems where most of neutral hydrogen resides after reionization).

On the other hand, a ratio of the the Hubble time to the average recombination time in a particular region of the universe is

$$\frac{t_H}{t_{\rm REC}} \approx 1.3 \left(\frac{1+z}{7}\right)^{3/2} \left(1+\langle\delta\rangle\right) C_R, \quad (3)$$

where $\langle\delta\rangle$ is the average overdensity in that region, and C_R is the recombination clumping factor in that region (Kohler et al. 2007), $C_R = \langle R(T) n_e n_{\rm H\,II}\rangle / (\langle R(T)\rangle \langle n_e\rangle \langle n_{\rm H\,II}\rangle)$.

Since the definition of the escape fraction of ionizing radiation from Gnedin et al. (2007) accounts for all local absorption, including high density gas inside a galaxy halo, which dominates the clumping factor, C_R cannot be large in the general IGM. More than that, the conclusion that reionization is complete by $z \approx 6$ comes primarily from the observations of the SDSS quasars (Fan et al. 2006, and references therein). The transmitted flux at $z \gtrsim 5.5$ comes mostly from the centers of large voids, where $(1+\langle\delta\rangle) \approx 0.1$ and $C_R \lesssim 10$. Equation 3 then implies that less than 2 ionizing photons per baryon (outside the virial radii of ionizing sources) are needed to satisfy the observational requirements. Of course, if the local absorption inside the virial radius (characterized by a large clumping factor C_R) is included, the required number of ionizing photons per baryon will be much higher; but then a correspondingly larger value for the escape fraction (which excludes local absorption) should be adopted.

That estimate is also consistent with the conclusion by

[6] $\Omega_M = 0.27$, $h = 0.72$, $n_S = 0.99$, $\sigma_8 = 0.90$

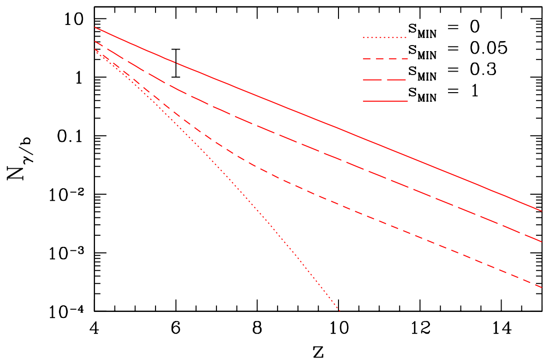

FIG. 4.— The total ionizing photon-to-baryon ratio as a function of redshift for the WMAP3 cosmology for different assumed values of the parameter $s_{\rm min}$: 0 (dotted line), 0.05 (short-dashed line, the fiducial value from Gnedin et al. (2007) simulations), 0.3 (long-dashed line) and 1 (solid line).

Miralda-Escudé (2003), who estimated that

$$\frac{1}{H}\frac{dN_{\gamma/b}}{dt} \lesssim 7$$

for $6 < z < 9$, which translates into $N_{\gamma/b} \lesssim 2.5$ if the contribution of sources beyond $z = 9$ is unimportant.

Thus, a requirement

$$1 < N_{\gamma/b}(z=6) < 3 \qquad (4)$$

appears to be a sensible criterion for the reionization of the universe by $z = 6$. The same condition has also been obtained by Bolton & Haehnelt (2007) from extrapolating the production rate of ionizing photons required to fit the observed evolution of the mean opacity of the Lyman-alpha forest to $z = 6$.

Thus, the WMAP1 cosmology is marginally sufficient to satisfy the condition (4), while the WMAP3 universe is well short of the needed amount of ionizing radiation at $z \approx 6$ by at least a factor of 2 (and, perhaps, as much as a factor of 10 if the value for the intrinsic break $r_{\rm int}$ is close to 6 than to 3, and the transition to low escape fraction occurs at $5\times10^{11} M_\odot$ rather than at $5\times10^{10} M_\odot$).

This, somewhat unexpected, result crucially depends on the main conclusion of Gnedin et al. (2007) that the escape fraction is very small for low mass galaxies. That conclusion is consistent with the observational measurements of the escape fraction by Fernández-Soto et al. (2003) and our knowledge of dwarf galaxies in the local universe, which are known to have large gas fractions and H I extend that exceeds the extend of the stellar disk. On the other hand, as Figure 4 shows, if the escape fraction is independent of the galaxy mass (*smin* = 1), the WMAP3 cosmology comfortably falls into the reionization requirement with $N_{\gamma/b}(z=6) \approx 1.5$.

It is, therefore, imperative to have the measurements of the escape fraction extended to even fainter galaxies and result of Gnedin et al. (2007) verified with higher resolution simulations and different numerical methods. Were it found that the escape fractions of dwarf galaxies are, indeed, negligibly small, then new, more exotic sources of ionizing radiation (Pop III stars, X-ray binaries, a new, previously unknown population of faint quasars, etc[7]) would need to be invoked to explain the (relatively) early reionization of the universe at $z \approx 6$.

I thank Hsiao-Wen Chen, Andrey Kravtsov, and Jordi Miralda for valuable comments and corrections to the original manuscript. I am also grateful to Andrey Kravtsov for the permission to use his halo mass function code free of charge. This work was supported in part by the DOE, by the NSF grant AST-0507596, and by the Kavli Institute for Cosmological Physics at the University of Chicago.

[7] But *not* the top-heavy IMF, since the conclusion presented in this paper is independent of the stellar IMF and does not require any assumption about a particular shape for the IMF.

REFERENCES

Bolton, J. S. & Haehnelt, M. G. 2007, ArXiv Astrophysics e-prints
Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2007, ArXiv e-prints, 707
Chen, H.-W., Prochaska, J. X., & Gnedin, N. Y. 2007, ArXiv e-prints, 707
Conroy, C., Wechsler, R. H., & Kravtsov, A. V. 2006, ApJ, 647, 201
Fan, X., Strauss, M. A., Becker, R. H., White, R. L., Gunn, J. E., Knapp, G. R., Richards, G. T., Schneider, D. P., Brinkmann, J., & Fukugita, M. 2006, AJ, in press
Fernández-Soto, A., Lanzetta, K. M., & Chen, H.-W. 2003, MNRAS, 342, 1215
Giallongo, E., Cristiani, S., D'Odorico, S., & Fontana, A. 2002, ApJ, 568, L9
Gnedin, N. Y., Kravtsov, A. V., & Chen, H.-W. 2007, ArXiv e-prints, 707
Hopkins, P. F., Richards, G. T., & Hernquist, L. 2007, ApJ, 654, 731
Kohler, K., Gnedin, N. Y., & Hamilton, A. J. S. 2007, ApJ, 657, 15
Leitherer, C., Schaerer, D., Goldader, J. D., Delgado, R. M. G., Robert, C., Kune, D. F., de Mello, D. F., Devost, D., & Heckman, T. M. 1999, ApJS, 123, 3
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Miralda-Escudé, J. 2003, ApJ, 597, 66
Razoumov, A. O. & Sommer-Larsen, J. 2006, ApJ, 651, L89
—. 2007, ArXiv Astrophysics e-prints
Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., & Erb, D. K. 2006, ApJ, 651, 688
Siana, B., Teplitz, H. I., Colbert, J., Ferguson, H. C., Dickinson, M., Brown, T. M., Conselice, C. J., de Mello, D. F., Gardner, J. P., Giavalisco, M., & Menanteau, F. 2007, ApJ in press (astro-ph/0706.4093), 706
Spergel, D. N., Bean, R., Dore', O., Nolta, M. R., Bennett, C. L., Hinshaw, G., Jarosik, N., Komatsu, E., Page, L., Peiris, H. V., Verde, L., Barnes, C., Halpern, M., Hill, R. S., Kogut, A., Limon, M., Meyer, S. S., Odegard, N., Tucker, G. S., Weiland, J. L., Wollack, E., & Wright, E. L. 2006, ArXiv Astrophysics e-prints
Spergel, D. N., Verde, L., Peiris, H., & et al. 2003, ApJS, 148, 175