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Bright Light from Dark Matter (Baryonic and Non-baryonic)

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Abstract Preliminary investigation of GALEX images of the diffuse ultraviolet background radiation suggests that part of the diffuse background represents red-shifted Lyman α recombination radiation from the intergalactic medium, which in turn would require, to maintain the observed high degree of ionization of the intergalactic medium, that the non-baryonic dark matter decay with the emission of an ionizing photon. Techniques for verifying this and for treating the data are described in some detail.

Key words: techniques: ultraviolet – cosmology: diffuse background

1 INTRODUCTION

With colleagues Jayant Murthy and Luciana Bianchi, and with the help of two students (P. Shalima and N. V. Sujatha) at the Indian Institute of Astrophysics, I am currently investigating the diffuse ultraviolet background radiation by means of a successful guest investigator proposal for NASA's GALEX mission.

The purpose of the present paper is to lay out our planned methods of treatment of our GALEX data by applying my software to publicly available GALEX Deep Imaging Survey ("Dis") images. These images may be downloaded by anyone from the MAST web site at the Space Telescope Science Institute: http://galex.stsci.edu/GR1/

The intent of our GALEX proposal was to test the idea (Henry 1991, 1999) that a substantial fraction of the diffuse ultraviolet background that is seen at moderate and high galactic latitudes originates neither in starlight scattered from dust, nor in the integrated light of faint galaxies, but instead is red-shifted Lyman α radiation from the intergalactic medium. If this should turn out to be true, it would of course be an extremely important result for cosmology and for cosmogony. In particular, the red-shifted Lyman α would be radiation from the baryonic dark matter in the universe, while if *that* is correct, this origin would require emission of ionizing radiation by the non-baryonic dark matter (to maintain the observed high degree of ionization of the intergalactic medium in the face of repeated rapid recombinations). Hence the title of this paper.

I present here my results for *two* of the fourteen GALEX Dis targets (Table 1). One of these, Dis-08, I have selected because the image turned out to contain a very substantial contribution from dust-scattered starlight, while the second, Dis-09, is chosen because (as we shall see) it contains almost *no* dust-scattered starlight, despite having a very strong diffuse UV background present—far more than could possibly be due to the integrated light of unresolved galaxies.

Thus, this preliminary investigation suggests that the project of Henry, Murthy, Bianchi, Shalima, and Sujatha, might well have exciting results.

2 THE GALEX IMAGES.

There are two GALEX cameras: the "FUV" camera images a band from 1300 Å to 1700 Å (corresponding to redshifts of 0.07 to 0.4) while the "NUV" camera images a band from 1700 Å to 3000 Å (redshifts of

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Table 1 The Two of the 14 GALEX Deep Imaging Survey Targets that I Analyse

Dis	Name	RA & Dec	ℓ & b	Δt	$E_{(B-V)}$
08	SIRTFFL_03	258.33 58.87	87.64 35.55	5558	0.029
09	SIRTFFL_00	259.13 59.91	88.86 35.04	23765	0.022

0.4 to 1.5). The redshifts are those of hydrogen Lyman α on the hypothesis which we expect eventually to test: that a substantial fraction of the detected signal is due to recombination radiation from the intergalactic medium.

The MAST web site provides images from both cameras, and also provides the same images with all point sources removed. It is the latter images, of course, that are of interest for the present project.

The angular resolution of the GALEX cameras is six seconds of arc, but in order to achieve the signal-to-noise that is necessary for our purposes, we have reduced the number of pixels by a factor of 900, the image being converted from 3840 $\times$ 3840 pixels to 128 $\times$ 128 pixels.

3 REMOVAL OF DUST-SCATTERED STARLIGHT

The field of view of each camera has diameter one degree (ignoring the outer edge of the field, where instrumental scattered light is clearly present). I have consulted the interstellar dust maps of Schlegel et al. (1998) in order to determine what fraction of the diffuse background signal in each image is due to dust-scattered starlight. I have created a map (Figure 1), using the data of Schlegel et al., which shows the dust distribution in the region that includes Dis-08 and Dis-09, the two images that I analyse in the present paper. These two images were selected as “typical,” in that one (Dis-08) is found to contain a considerable amount of dust-scattered starlight (principally in the arc that is clearly visible in Figure 1), while the other contains almost *no* dust-scattered starlight.

The result of my analysis appears in Figure 2, where for both the FUV and NUV images of Dis-08, the ultraviolet brightness is plotted against the E_{B-V} values from Schlegel et al. In Figure 3 is given the same information for Dis-09.

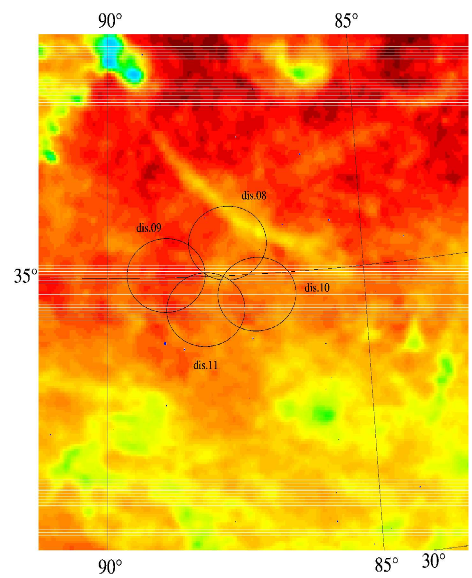

Fig. 1 Dust distribution map from Schlegel et al. (1998) showing the locations of four GALEX Deep Imaging Survey (“Dis”) targets. In the present paper I present results for Dis-08 (which has a strong arc of dust in the field of view) and Dis-09, which is largely free of dust. The circles represent the full field of view (1.26°) of the GALEX cameras.

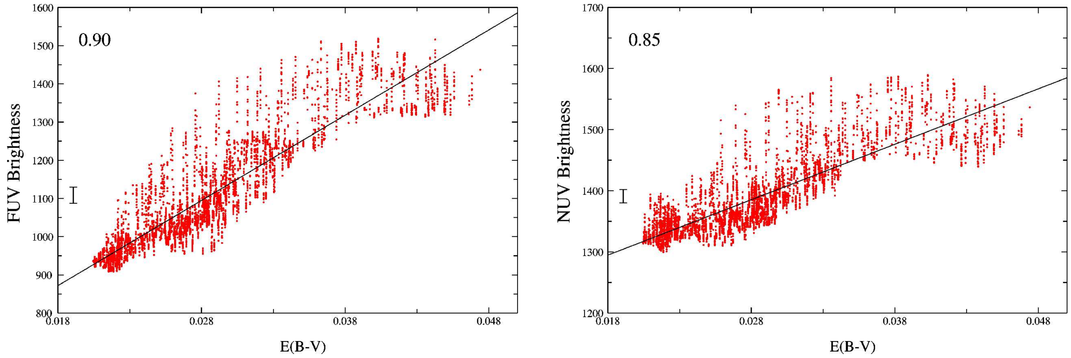

Fig. 2 For each pixel in the Dis-08 GALEX images, I plot the ultraviolet brightness against the value of E_{B-V} from Schlegel et al. 1998. The NUV brightness has been reduced by 350 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} to allow for zodiacal light. The good correlations (0.90, 0.85) prove that there is dust-scattered starlight present in the image, while the non-zero intercept shows that there is a great deal of additional UV light that is *not* dust-scattered starlight. The reader should also notice that for both the NUV and the FUV images, the *scatter* in brightness, as a function of E_{B-V}, is much greater than the standard error in a single pixel (a typical error bar is shown).

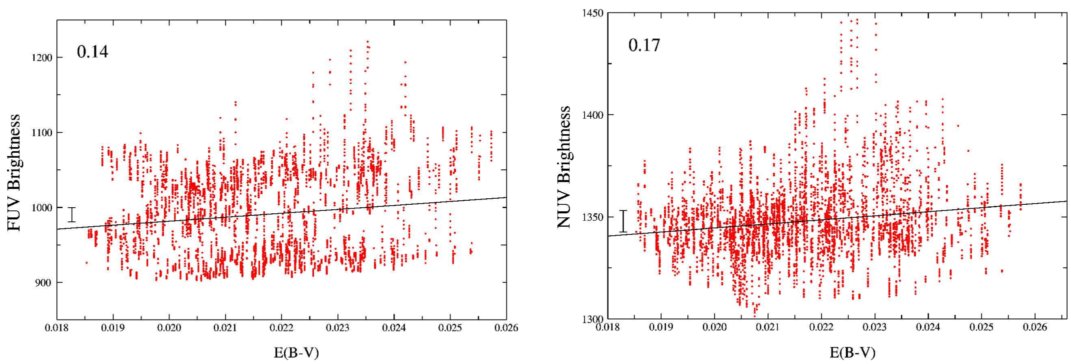

Fig. 3 The same as Figure 2, but now for Dis-09. In contrast with the previous figure, we see that there is essentially *no* correlation of the Dis-09 ultraviolet signal with E_{B-V}. We conclude that the signal is almost entirely due to something other than starlight scattered from dust. (In the case of the NUV image, part of that excess is merely zodiacal light, but from all NUV data I have removed 350 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} to allow for that.)

The correlations for FUV and for NUV for Dis-08 are very strong, and show conclusively that there is a considerable signal in these images that must represent dust-scattered starlight. But, it is also apparent that there is, in addition, signal that *cannot* be due to dust-scattered starlight: first, there is a non-zero intercept to the least-squares fit to the data, indicating that even were there *no* dust, there would still be a strong signal; and second, the scatter about the least-squares straight-line fit is much greater than the statistical uncertainty in the UV brightness determination for each pixel (a typical error bar giving that statistical uncertainty is shown in each plot).

In extreme contrast, the correlations for Dis-09 that appear in Figure 3 are very weak: indeed, almost non-existent. It is clear that there is almost *no* signal in Dis-09 that is due to dust-scattered starlight. And, again, the scatter is very large compared with the statistical uncertainty associated with each point, indicating that our factor 900 expansion of the pixel size has allowed us to detect significant structure in the image; structure that, in the case of Dis-09, is not at all correlated with the amount of dust in that direction.

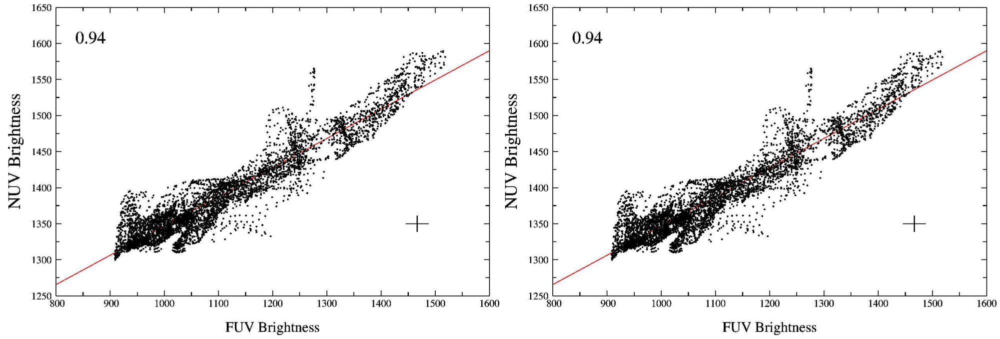

Fig. 4 The pixel-by-pixel correlation between the FUV and the NUV image for Dis-08. There is a much stronger correlation (0.94) before the removal of dust-scattered starlight, but there is certainly still a *strong* correlation (0.79) afterward. Is this because the removal process is imperfect, or because the signal that is *not* due to dust- scattered starlight is correlated between the two images? There is no way to be certain. That is why the Dis-09 observation, which is *free of* dust-scattered starlight, is so important.

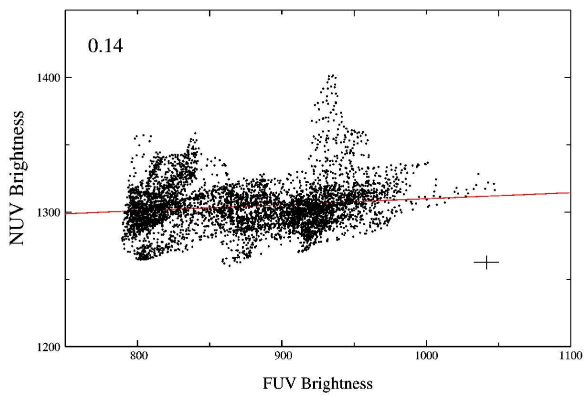

Fig. 5 Here is the pixel-by-pixel correlation for Dis-09, after removal of the very small amount of dust-scattered starlight. The correlation coefficient is 0.14 while before removal it was 0.15. This establishes that the ultraviolet background radiation that is *not* due to dust-scattered starlight is uncorrelated between the NUV and FUV images, which is difficult to understand other than under the hypothesis that the signal is from the intergalactic medium.

4 CORRELATION BETWEEN THE FUV AND NUV IMAGES—DUSTY TARGETS

In Figure 4, I show the pixel-by-pixel correlation between the FUV and NUV images of Dis-08 before and after the removal of dust-scattered starlight. If, in some GALEX image, it should happen that almost *all* of the signal were due to dust-scattered starlight, we would expect an almost perfect correlation between the two images before removal the of dust-scattered starlight, and, of course, no residual. In fact (Figure 4) for the case of Dis-08 we see a very strong correlation (correlation coefficient 0.94) before the removal of dust-scattered starlight), but a still very strong correlation (0.79) between the two images for the strong residual signal that remains *after* the removal of dust-scattered starlight.

How are we to interpret this residual signal? The problem is that the resolution of the Schlegel et al. dust maps is much worse than the resolution of the GALEX images, and evidently the variation in dust across a single Schlegel element is considerable. Thus my removal of dust-scattered starlight is very far from perfect.

Table 2 GALEX Target Ultraviolet Brightnesses (photons cm^{-2} sr^{-1} s^{-1} Å^{-1})

Dis	FUV (mean)	FUV (intercept)	NUV (mean)	NUV (intercept)	Correlation
08	1109	470	1391	1132	0.79
09	990	876	1348	1305	0.14

So what is the conclusion regarding Dis-08? It is that these images (and similar images for other GALEX targets that turn out to have a substantial dust-scattered starlight component to them) can only be of *qualitative* interest, in our main task of attempting to ascertain the nature of that part of the image that is *not* of dust-scattered-starlight origin. Fortunately, such dust-dominated images turn out to be only approximately 1/3 of the Dis images.

5 CORRELATION BETWEEN THE FUV AND NUV IMAGES—DUSTLESS TARGETS

My presentation of the GALEX Dis-08 dusty target in this paper was mainly for the purpose of getting it *out of the way:* dust-scattered starlight is only of *modest* interest; a strong UV background that is *not* due to dust-scattered starlight is (potentially) of very much greater interest. With Dis-08, my intention was simply to demonstrate that I can reliably identify targets that are substantially contaminated with dust-scattered starlight, so that such targets can subsequently, largely, be ignored.

Of far greater interest are targets, such as Dis-09, that turn out (Figure 3) to have little or no dust-scattered starlight. Almost all of the very strong UV backgroud in Dis-09 is *not* due to dust-scattered starlight. What can it be?

Well, what *could it* be? Apart from the idea of radiation from the intergalactic medium, almost the only source that has been suggested is the integrated light of faint galaxies. That signal has been estimated by Armand, Milliard, & Deharveng (1994) to be in the range 40 to 130 photons cm^{-2} sr^{-1} s^{-1} Å^{-1}, while Gardner, Brown, & Ferguson (2000) have actually measured the integrated background using HST, finding a lower limit of 144 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} and and upper limit of 195 photons cm^{-2} sr^{-1} s^{-1} Å^{-1}.

Well, the observed diffuse ultraviolet background in Dis-09 is (Table 2) *very much larger* than any of these predicted or observed values for the integrated light of faint galaxies, which therefore may be conclusively eliminated as the source the observed radiation for Dis-09.

One other predicted source of diffuse UV background should be mentioned, for completeness, and that is two-photon emission from metastable hydrogen atoms in the interstellar medium. However, that source has been estimated by Deharveng, Joubert, and Barge (1982) to contribute only about 75 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} to the diffuse ultraviolet background, which means that this source, too, can be eliminated as a possible source for the strong radiation that is observed from Dis-09.

6 THE FUV AND NUV IMAGES OF DIS-08

In Figures 6 and 7 I show the actual FUV images (before and after removal of signal identified as being due to dust-scattered starlight) for the dusty Dis-8 target. Please compare with Figure 1. The arced ridge that is apparent in Figure 1 is the pronounced rise that is apparent on the right in both Figure 6 and Figure 7. Keep in mind that in Figure 1 the full field of view of the GALEX cameras is shown, while in Figures 6 and 7, only the data from the central one degree of the field is plotted, to avoid the substantial instrumental scattered light that is near the edge of each GALEX image.

In Figures 8 and 9, similarly, I show the actual NUV images for the same dusty target, Dis-08. In these figures, and in the preceding figures, it is apparent that the removal of dust-scattered starlight appears to be incomplete. But it cannot be excluded that this is coincidence, and that the additional signal, which is *not* due to dust-scattered starlight, just happens to be similarly distributed. For this reason the GALEX images of dusty targets are of limited value.

7 THE FUV AND NUV IMAGES OF DIS-09

Finally, in Figures 10 and 11, I present the FUV and NUV images, respectively, for the target Dis-09 that has a very large UV diffuse background signal but that is almost entirely free of dust-scattered starlight, as has been demonstrated in Figure 3. No dust-scattered starlight has been removed from these images.

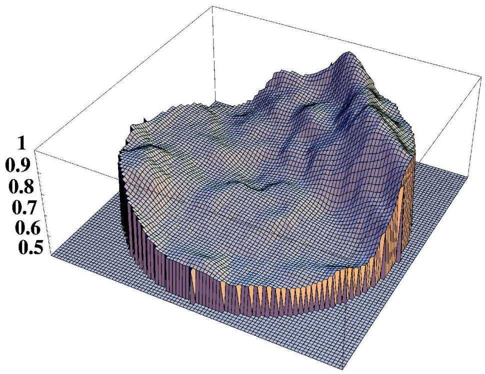

Fig. 6 This is the FUV image of Dis-08 before the removal of signal that is identified (Fig. 2) as starlight scattered from interstellar dust.

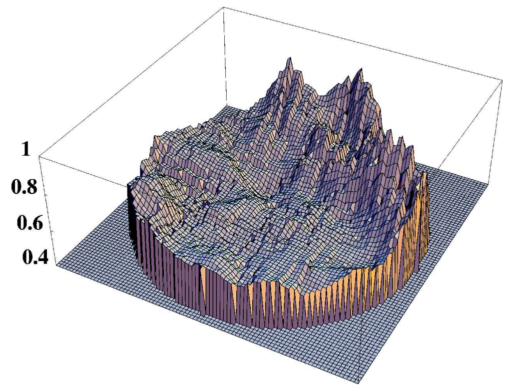

Fig. 7 This is the FUV image of Dis-08 *after* the removal of signal that is identified (Fig. 2) as starlight scattered from interstellar dust. Comparison of this image with that of Figure 7 suggests, but does not prove, that the process of removal of signal due to dust-scattered starlight is very imperfect, as the main residual after removal is located exactly where the main removed component was located.

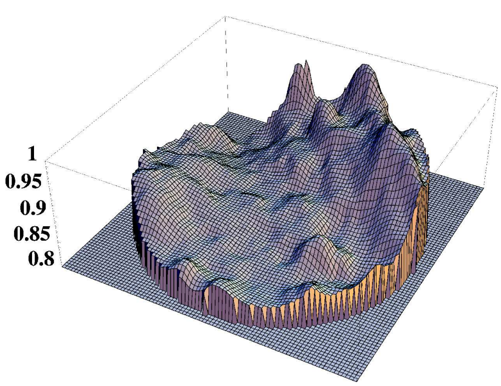

Fig. 8 This is the NUV image of Dis-08 before the removal of signal that is identified (Fig. 2) as starlight scattered from interstellar dust.

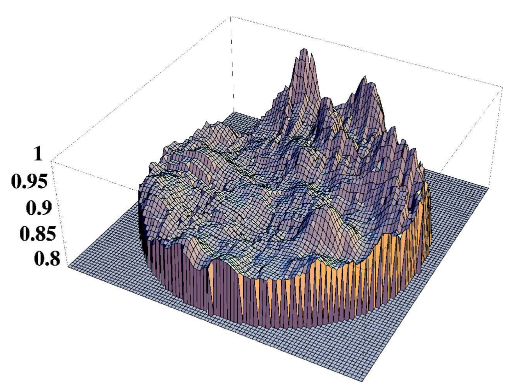

Fig. 9 This is the NUV image of Dis-08 *after* the removal of signal that is identified (Fig. 2) as starlight scattered from interstellar dust.

This demonstrates the quality of data that will be available to us in attempting to determine whether this radiation is Lyman α recombination radiation from the intergalactic medium. Figure 5 shows essentially no correlation at all between the diffuse ultraviolet background radiation in the FUV and NUV images of Dis-09, which is exactly what is predicted on the recombination radiation hypothesis, because essentially totally different ranges of redshift are observed by the two GALEX cameras. Before one can come to a firm conclusion regarding the intriguing FUV and NUV images seen in the GALEX Dis targets, one must ask whether the structure that appears in the figures is real, and if it is real, if it is of astronomical origin. The most powerful way to tackle that question is to work with subsets of the data, to test for correlation. Such subsets will be available to me and my colleagues for our own guest investigator data, and we look forward to completing such analysis. For example, geophysical effects of some kind conceivably could

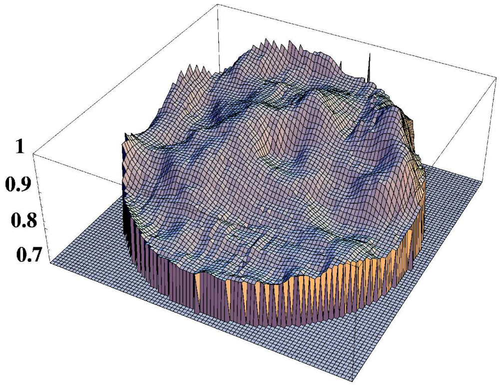

Fig. 10 This is the FUV image of Dis-09, which is almost entirely free of dust- scattered starlight. Structure is present that, if real, is perhaps associated with the intergalactic medium. Note the presence of small-scale structure, and also the presence of a much larger scale slope across the field, suggestive of structure larger than the field. In all of the images, we only show the central one degree, thus avoiding instrumental scattered light which is present at the edges of the FUV and NUV fields of view.

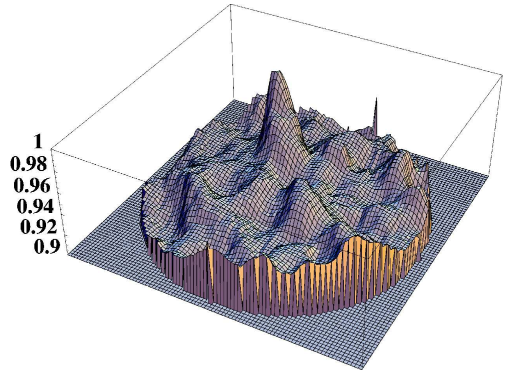

Fig. 11 This is the NUV image of Dis-09, also almost entirely free of dust- scattered starlight (Fig. 3). Again interesting structure appears in the image which if real perhaps can be attributed to the intergalactic medium. Similar (but not identical) structures appear in all 14 of the Dis FUV and NUV images. In the case of the FUV images, but not the NUV images, there is typically in addition to smaller-scale structure, a general slope in diffuse background intensity, with the direction of slope varying from target to target.

contaminate the data. Additionally, our guest investigator data involves targets chosen by us as particularly suitable for testing our extragalactic recombination radiation hypothesis. In particular, the main basis for our suggestion that hydrogen Lyman α recombination radiation might be the source of the diffuse UV background that is universally observed longward of 1216 Å is the fact that Murthy et al. (1999) observed many locations where, shortward of Lyman α, only an upper limit of 30 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} is observed, which is clearly suggestive that the longer-wavelength radiation is red-shifted Lyman α. Some of these low-background targets are included in our guest investigator observing plan. We expect to complete our guest investigator work over the next several months.

Acknowledgements This work was funded by Maryland Space Grant Consortium.

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DISCUSSION

JOHN BECKMAN: The ionization you require might not need radiative decay of the non-baryonic dark matter: see Zurita, Beckman, and Rozas (2002).

HENRY: Thank you; I will investigate that.