Cume 323 based on the paper "Abundant dust found in intergalactic space" by Xilouris etal, 2006, ApJ L107, Cume given by R. Walterbos

Maximum possible points: 60 points. Expected passing grade: 42 points or more.
The first 5 questions should not take too much time. The last two require more of your time to give a critical reading of the main results and conclusion in the paper, so try not to wait till the last 15 minutes answering them.

1. (10 pts) The paper mentions a "starburst-driven superwind". Describe what that is, how it originates, how we may detect such winds.

Key points: high star formation concentrated in central region of galaxy, massive stars create stellar winds plus supernova explosions. The concentration of this mechanical energy input into the ISM causes the denser gas to pile up in "walls" or "chimneys", while the hot gas from the supernova explosions is highly overpressured and will want to escape into the halo. The outflow of hot gas entrains cooler gas clouds and the radiation of the stars will ionize the chimney walls. We can observe the superwind principally through:

- imaging and spectroscopy in Halpha and other emission lines to delineate the chimney walls and motions of the warm gas
- X-ray observations to image the hot gas that is escaping into the halo

2. (5 pts) In section 2 they describe the observations. Confirm the 0.29 square degree field size from the information they give there.

pixel size: 0."33
area covered: 4 CCDs, each is 2048x4100 pixels
$\rightsquigarrow$ 0.282 sq. degrees.

3. (5 pts) Why do they need to observe "control fields"? How are the data from it used?

The main technique in the paper is to compare the colors of background galaxies seen through the tidal HI streams with those that would be observed in the absence of such streams. The control fields serve to provide the latter. The data from it are used to provide the intrinsic galaxy colors that are subtracted from the galaxy colors observed through the tidal streams to get a net reddening. The complication is that both control and data fields have varying Galactic foreground extinction which also needs to be corrected for.

4. (5 pts) Define "airmass"? Why do they need to observe calibration stars at different airmass?

Airmass is a measure of abs. of light along a path in the Earth's atmosphere. We define airmass =1 in direction of zenith. In plane-parallel atmosphere, airmass increases then as sec(z) with z = "zenith distance" expressed as an angle away from zenith.
We can extrapolate a flux to flux as measured outside atmosphere through measurements of same standard star(s) at different airmasses. This has to be done at all wavelengths of interest.

5. The dust extinction in the situation in the paper acts as a foreground screen of dust. You can ignore scattering of light by dust in this case (or just lump it together with absorption).

a. (10 pts) What is the radiative transfer equation for a source with an intrinsic intensity I(0) observed through an absorbing foreground screen? Write it first with use of the absorption coefficient, α, then in terms of the optical depth τ.

$$\frac{dI}{ds} = -\alpha I, \quad \text{define } \tau \equiv \int_0^l \alpha \, ds \quad \text{along path length}$$

What is the solution of this radiative transfer equation?

$$I = I_0 e^{-\tau}$$

b. (5 pts) Derive how τ is related to the extinction in magnitudes at the same wavelength.

$$A_\lambda \equiv -2.5 \log \frac{I_\lambda}{I_{0,\lambda}} = -2.5 \log (e^{-\tau_\lambda}) = +1.086 \, \tau_\lambda$$

c. 5 pts) How is E(B-V) defined in terms of the extinction in magnitudes? Why is E(B-I) larger than E(B-V)?

$$E(B-V) \equiv A_B - A_V$$

E(B-I) is larger since it spans a larger wavelength range than E(B-V) so the extinction at I is less than at V, and the color change from B to I is larger than from B to V.

6. (10 pts) What are some of the weaknesses of their analysis that may make the results somewhat questionable? To answer this, first take a critical look at what they have to do to get their results and look at Figures 1, 3, and the information given in Section 2. There is not so much a perfect answer here, but I want to see your ability to analyze a piece of research critically and see if you can zoom in on some of the main factors that affect the interpretation.

Correcting for foreground extinction from the MW is the biggest probably. Note that the corrections for control fields from the Schlegel maps are of the same order as the effect they find (especially for Field 3). Other points: can galaxy population fluctuations between fields be ruled out? Or variations in sensitivity limits for the fields? One has the distinct impression that Fields 1 and 2 have more galaxies than the control fields. More galaxies could mean going to higher redshift and picking up redder galaxies. How did they calculate the average HI column densities from the Yun data for each field? The scatter in their results in Figure 3 in terms of inferred dust-to-gas ratio at similar gas column densities is quite large compared to the stated uncertainties. Why would there be so much scatter, and a tendency for lower gas content to have relatively higher dust/gas ratio?

7. (5 pts) Discuss their idea that the additional dust, if real, would be due to an outflow of dust from M82. Why do they have to postulate this rather special origin for the dust rather than e.g. in situ dust formation in the existing HI gas? How could their conclusion be tested further? Does it look a solid conclusion given the data and results they have in hand?

Why would the dust distribution coincide with the HI tidal tails which have a different origin? Why also would the highest apparent dust-gas ratio be found in the fields farthest from M82 (in Field 1, not Field 2, judging from their comment in Figure 3 regarding Field 2 ?

The problem with in situ dust formation is that we likely don't have the metals (and gas concentrations) to build up "super-solar" ~~metal~~ dust/gas content.

Tests: high sensitivity FIR imaging to map dust (very hard, but possible in local areas), detection of dust through scattered light in UV (Galex satellite has some results), deeper galaxy counts to increase statistical significance, searching for evidence of dust in M82 outflow directly (e.g. through FIR & MIR mapping).

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ABUNDANT DUST FOUND IN INTERGALACTIC SPACE

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ABSTRACT

Galactic dust constitutes approximately half of the elements more massive than helium produced in stellar nucleosynthesis. Notwithstanding the formation of dust grains in the dense, cool atmospheres of late-type stars, there still remain huge uncertainties concerning the origin and fate of galactic stardust. In this Letter, we identify the intergalactic medium (i.e., the region between gravitationally bound galaxies) as a major sink for galactic dust. We discover a systematic shift in the color of background galaxies viewed through the intergalactic medium of the nearby M81 group. This reddening coincides with atomic, neutral gas previously detected between the group members. The dust-to-H I mass ratio is high (1/20) compared to that of the solar neighborhood (1/120), suggesting that the dust originates from the center of one or more of the galaxies in the group. Indeed, M82, which is known to be ejecting dust and gas in a starburst-driven superwind, is cited as the probable main source.

Subject headings: dust, extinction — galaxies: individual (M81, M82, NGC 3077) — galaxies: interactions — intergalactic medium

Online material: color figures

1. INTRODUCTION

The mass contained within galactic dust is only 1% that contained within interstellar gas and amounts to less than 0.1% of the total mass of the galaxy. Nevertheless, galactic dust has a major influence on both our perception of galactic structure (through extinction) and the processes taking place in the interstellar medium. Indeed, dust grains provide the reaction sites necessary for the formation of complex molecules (Herbst 2001) and constitute the building blocks of planet formation (Greaves et al. 2004).

The balance between the formation and the removal of dust in spiral galaxies, like our own, is far from clear. Cool, dense atmospheres of stars that have left the main sequence (red giants) are currently identified as a primary source of dust in our own Galaxy (0.04 $M_\odot$ yr^{-1}; Whittet 1992). However, the destruction rate of dust grains from interstellar shocks is predicted to be relatively high, suggesting that other primary dust sources are yet to be identified (Seab 1988).

Intense star formation in galactic disks is known to eject dust several kiloparsecs out of the main stellar plane, but thus far it is not clear whether such material escapes entirely from the galaxy or returns to the main disk in a galactic-scale, convective, mixing process (Heckman et al. 1990; Howk & Savage 1997). In this Letter, we examine the photometric color of background galaxies viewed through the intergalactic medium of the M81 group. Any systematic reddening of the background objects, compared to the same population viewed adjacent to the group, reveals the presence of dust residing between the group members (galactic dust absorbs more blue than red light, thus both attenuating and reddening light from background sources). The M81 group is a suitable testing ground for theories of dust loss in the intergalactic medium for several reasons. First, it constitutes one of the nearest examples of a tidally interacting ensemble of galaxies (distance 3.6 Mpc; Freedman et al. 1994). Second, copious amounts of neutral atomic hydrogen gas have been found connecting the various group members in a series of bridges and filaments (Yun et al. 1994). Third, one of the three main galaxies in the group (M82) is known to be expelling dust and neutral gas away from its starburst core toward the intercluster medium (Ichikawa et al. 1994; Alton et al. 1999; Engelbracht et al. 2006).

Comparing the mean color of background objects is well established as a technique for probing dust outside the main stellar disk (Zaritsky 1994; Lequeux et al. 1995; Boyle et al. 1988; Holwerda et al. 2005). However, the advent of large, optical imaging arrays, which incorporate several contiguous CCDs, permits sufficient numbers of distant galaxies to be detected that we can begin to trace the distribution of foreground dust rather than simply its mean optical depth.

2. OBSERVATIONS AND DATA ANALYSIS

The Wide-Field Camera (WFC) mounted on the 2.5 m Isaac Newton Telescope (INT), La Palma, consists of four 2048 × 4100 pixel EEV CCDs (0.″33 pixel^{-1}) and provides a field of view of 0.29 deg^2. During four dark nights at the INT (2004 March), we have used the WFC to observe the M81 group in the Johnson *B* and the Sloan *I* filters (wavelengths of 436 and 767 nm, respectively). Of a total of four fields observed, two "on-source" regions (F1 and F2) correspond to parts of the group where extended H I emission has been detected by Yun et al. (1994). The remaining two fields were situated approximately 4° from the center of the group and constituted control fields (F3 and F4). Figure 1 shows the position of our chosen fields, and Table 1 provides a summary of the observations.

The debiasing, flat-fielding, and trimming of the frames obtained with the WFC were carried out using standard IRAF and MIDAS image software packages. Fringes in the *I* band, at a level of ≃4%, were removed by observing blank sky fields containing relatively few sources on each night of observation and for multiple positions in the sky. During each night, three or four standard star fields (Landolt 1992) were observed in different air masses, and the measurements were fitted with a

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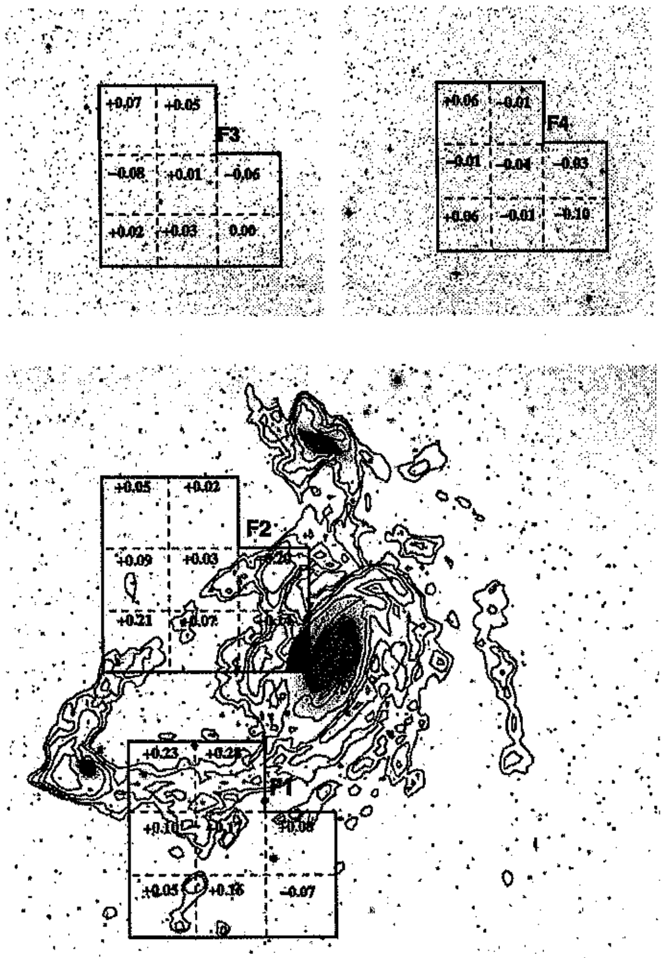

FIG. 1.—Map of the M81 group (1°.8 × 1°.8) showing the atomic, neutral hydrogen detected by Yun et al. (1994) as contours (3×10^{19} cm^{-2} × 2") and a B-band image as gray scale (from the Digitized Sky Survey). Note that extensive, diffuse gas is present outside the optical disks. The position of the WFC is outlined as a solid line. F3 and F4 constitute control fields, while F1 and F2 have been chosen to coincide with significant diffuse gas (note that the shaded part of F2 in the bottom right-hand corner is dominated by emission coming from the main body of M81 and was therefore masked and neglected from the further analysis). Background objects detected in each field are divided into eight subfields, and the $B - I$ excess with respect to the color of the control population is indicated in each box. [*See the electronic edition of the Journal for a color version of this figure.*]

three-term calibration equation (photometric zero point, air mass, color). In this way, photometric accuracy, on any given night, is estimated to be 0.02 and 0.01 mag in the B and I bands, respectively. Our limiting magnitudes in B and I are 27 and 24, respectively.

The photometrically calibrated WFC images were processed using the SExtractor software (Bertin & Arnouts 1996), which allows resolved objects of comparatively low surface brightness (galaxies) to be separated from point sources of high surface brightness (foreground Galactic stars). Cosmic rays are eliminated by imposing a minimum radius of 4 pixels or 1".32 for a bona fide detection (threshold at which surface brightness decreases to 50% of its maximum value). We have followed previous authors in using SExtractor with the CLASS_STAR parameter set to 0.92, but, for all fields, the successful separation of galaxies from stars was assured by visual inspection by plotting magnitude against half-light radius (stars appear as a well-defined locus in such a plot). The galaxy counts in our fields (objects per square degree per magnitude) were in excellent agreement with those previous published in deep surveys (Metcalfe et al. 2001). Typically, ~5000 galaxies were detected in both bands (B and I) for each of the four fields.

After galaxy-star separation, the next step was to determine the $B - I$ color of the background objects. An important preliminary in this process was the subtraction of foreground reddening associated with dust in the Milky Way. This was achieved by referring to maps of Galactic $B - V$ color excess [$E(B - V)$] along lines of sight to each of our fields (Schlegel et al. 1998) and applying a Galactic reddening law to convert $E(B - V)$ to $B - I$ color excess [$E(B - I) = 2.23E(B - V)$]. For each field, foreground $E(B - V)$ was sampled for eight constituent subfields (12′ × 12′), and the mean value was used to correct the $B - I$ colors for background objects detected in that particular field. The corrections in $B - I$ were -0.163, -0.120, -0.234, and -0.116 for F1, F2, F3, and F4, respectively, with a typical dispersion of 0.038 (rms). Along with the photometric error (0.026 mag) of the Galactic $E(B - V)$ maps (Schlegel et al. 1998), the total uncertainty for the subtraction of the foreground Galactic reddening becomes 0.046 mag.

3. RESULTS

In Figure 2 we show the histograms of the $B - I$ color for the background galaxies detected in each subfield. A smooth Gaussian function was fitted to the peak of each histogram to yield an average $B - I$ color. The typical uncertainty of the peak value of the Gaussian, as determined by the fitting procedure, is 0.02 mag. For the control fields, F3 and F4, the mean $B - I$ was recorded as 1.935 ± 0.048 and 1.920 ± 0.049, respectively, indicating a $B - I$ color for the background population of 1.928 ± 0.035. This color is consistent with that found in deep imaging surveys (Driver et al. 1994).

For the on-source subfields, comprising F1 and F2, values in excess of 1.928 indicate reddening by dust residing in the intergalactic medium. Taking into account both the uncertainty of the $B - I$ color for the background population (0.035 mag) and the uncertainty of the average $B - I$ color of the on-source fields (0.02 mag), the uncertainty in the $B - I$ color excess of

TABLE 1
A SUMMARY OF THE OBSERVATIONS

Field	R.A. (J2000.0)	Decl. (J2000.0)	Observation Date	Exposure Time (B band)	Exposure Time (I band)	Seeing (arcsec)
F1	10 00 00.5	68 32 36.5	2004 Mar 18	160	85	1.3
F2	10 00 35.1	68 19 39.8	2004 Mar 20	165	60	1.2
	10 00 35.1	68 19 39.8	2004 Mar 21	20	35	1.6
F3	10 30 55.1	72 14 35.9	2004 Mar 19	80	30	1.4
	10 30 55.1	72 14 35.9	2004 Mar 20	100	55	1.2
F4	09 25 46.6	72 17 02.9	2004 Mar 21	180	90	1.6

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Exposure time is given in minutes.

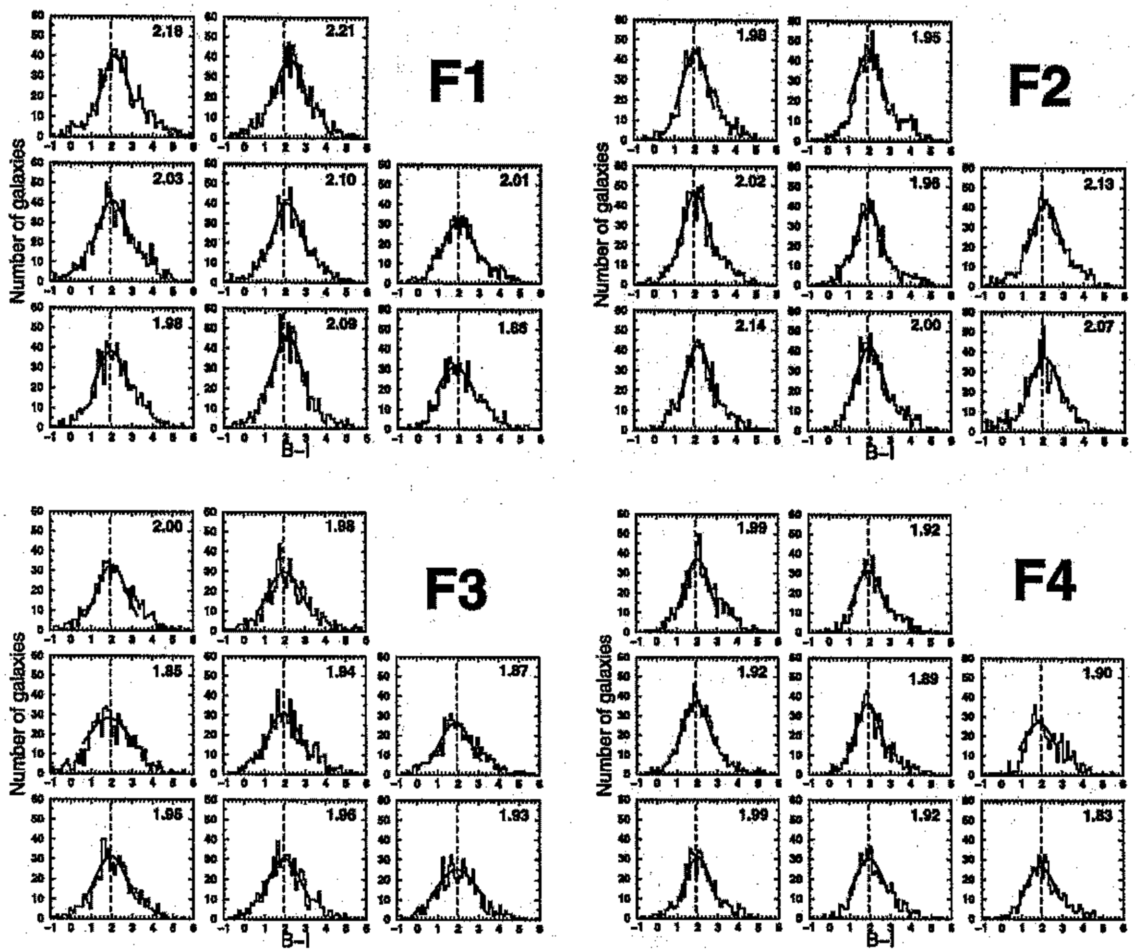

FIG. 2.—$B - I$ histogram of the background galaxies detected in each of the four fields. A Gaussian has been fitted to the peak of the distribution in each subfield in order to estimate the mode average (the latter is shown in the top right in each box). [*See the electronic edition of the Journal for a color version of this figure.*]

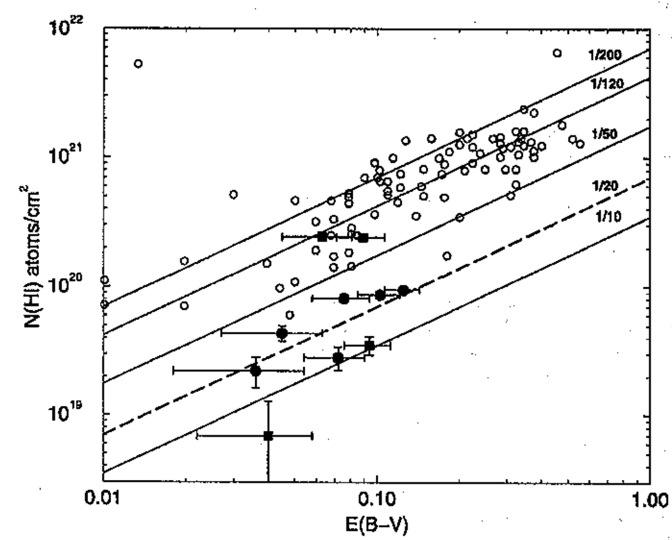

FIG. 3.—Surface density of atomic hydrogen [N(H I)] vs. color excess [$E(B - V)$]. Open circles correspond to measurements for the Milky Way close to the solar circle (Bohlin et al. 1978). These are compared with the corresponding values that we record for the on-source fields F1 and F2 (*filled circles and filled squares, respectively*) where significant reddening has been detected. Parallel lines indicate different dust–to–H I mass ratios. The two uppermost points for F2 are known to correspond to areas of low metallicity (Makarova et al. 2002).

the galaxies in our fields become 0.04 mag. Figure 2 reveals 10 subfields in F1 and F2 where such an excess is statistically significant (shift ≥0.08 mag, i.e., ≥2 σ). Notably, the greatest reddening coincides with the densest concentrations of atomic hydrogen in F1 and F2 and thus indicates a V-band extinction (A_V) as high as 0.39 mag (using a total to selective extinction $R_V = 3.08$; Pei 1992). The excesses with respect to the control fields are indicated in Figure 1 (the number shown in each subfield).

The mass ratio of dust to gas is known to correlate with heavy metal abundance, at least for the Milky Way and other members of the Local Group (Issa et al. 1990). Thus, for subfields where significant reddening is detected, we have plotted the dust–to–H I mass ratio and compared with the corresponding value in the solar neighborhood (see Fig. 3). The parallel lines in this plot indicate different dust–to–H I mass ratios assuming a value of 1/120 for the solar neighborhood (Sodroski et al. 1997; see the caption to Fig. 3 for more information on the symbols). The uncertainty in the surface density of the atomic hydrogen is derived by using a 0.8 mJy beam^{-1} rms as indicated in Yun et al. (1994), while the uncertainty in $E(B - V)$ is 0.018 [note that we have adopted a Galactic extinction law to convert from $B - I$ to $B - V$ excess $E(B - I) = 2.23E(B - V)$]. The intergalactic medium of the M81 group appears to be dust-rich with an average dust–to–H I mass ratio of 1/20, with values typically ranging between 1/10 and

1/50 (note that the two uppermost points for F2 in Fig. 3 are known to correspond to areas of low metallicity; Makarova et al. 2002). This value is approximately 6 times higher than that of the solar neighborhood (1/120; Sodroski et al. 1997).

4. DISCUSSION AND CONCLUSIONS

The implication of our finding (relatively high dust–to–H I mass ratio in the intergalactic space) is that the intergalactic material originates from a metal-rich environment since the outskirts of spiral galaxies such as M81 are epitomized by dust-to-gas mass ratios of less than the solar level (Cuillandre et al. 2001; Lequeux et al. 1995) and metallicities several times lower than the solar abundance (Vila-Costas & Edmunds 1992). Indeed, at the D_{25} radius (12′) of M81 (the optical "edge" of the stellar disk), the metallicity has been measured as $\frac{1}{4}$ solar (Vila-Costas & Edmunds 1992), implying that if the intercluster material had been drawn out from the peripheries of M81, it would have a dust-to-gas ratio of 4 times *less* than solar rather than our estimate of 6 times *higher*. Equally, we can show that the reddening we have detected cannot be attributed simply to the interstellar dust of M81 extending to extraordinarily large radii. Assuming a maximum *V*-band optical depth of 5 for the center of M81 (e.g., Alton et al. 2001) and a maximum radial, exponential scale length for interstellar dust of 5 kpc (e.g., Xilouris et al. 1999), the *V*-band optical depth in the subfields of F1 closest to M81 (~25 kpc) should not exceed $5\exp(-25/5) = 0.034$. The corresponding *V*-band extinction (0.037 mag) is nearly an order of magnitude lower than the attenuation we record for this region ($A_V = 0.24$ mag).

Given the relative abundance of the intergalactic dust with respect to the hydrogen gas, we postulate the center of M82 as a likely source for the dust. An energetic, starburst-driven outflow is known to be entraining up to $10^7\ M_\odot$ of dust away from the stellar disk toward the intergalactic medium (Alton et al. 1999). Simulations of the tidal interaction within the M81 group indicate that any material ejected by M82 is likely to be well dispersed across the intergalactic medium in the current configuration (Yun 1999). The total H I gas residing outside the galactic disks of the group is $9.6 \times 10^8\ M_\odot$ (Yun et al. 1994). Thus, for a dust–to–H I mass ratio of 1/20 (Fig. 3), we infer a total dust mass for the intergalactic medium of $4.8 \times 10^7\ M_\odot$. This is equivalent to the total amount of dust contained within a typical spiral galaxy such as M81 (Stickel et al. 2000). Assuming that M82 constitutes the remnants of a spiral galaxy that has been violently disturbed by its tidal encounter with the other group members (its current irregular morphology bears testament to this violent collision), the ensuing period of starburst-driven outflow appears to have been a highly effective mechanism for removing grains from the stellar disk.

Although, currently, starburst activity appears to occur in only one in 10 galaxies, the phenomenon is believed to be far more common at earlier epochs in the lifetime of the universe (Heckman et al. 1990). Our results imply, therefore, that the intergalactic medium is a significant sink for dust grains originating in galactic disks. This dust, together with the vast amounts of gas residing in these areas, can be used for the formation of tidal dwarfs, at least in areas close to the galactic disks (see Makarova et al. 2002). The grain properties (i.e., sizes and composition) as well as kinematical information on the dust grains and the gas are important parameters to study the fate of the material present in the intergalactic space between the galaxies of the M81 group. Several workers detect a systematic deficit in the density of quasars along lines of sight to clusters of intermediate redshifts ($z \simeq 0.1$) consistent with extinction levels close to that found in the present study (Boyle et al. 1988). This implies that the intergalactic nature of the copious dust we have detected in the M81 group is not unusual.

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