Searching for the Precursors of Life in External Galaxies

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Abstract.
Are the organic molecules crucial for life on Earth abundant in early-epoch galaxies? To address this, we searched for organic molecules in extragalactic sources via their absorption features, known as diffuse interstellar bands (DIBs). There is strong evidence that DIBs are associated with polycyclic aromatic hydrocarbons (PAHs) and carbon chains. Galaxies with a preponderance of DIBs may be the most likely places in which to expect life.

We use the method of quasar absorption lines to probe intervening early-epoch galaxies for the DIBs. We present the equivalent width measurements of DIBs in one neutral hydrogen (H\textsubscript{i}) abundant galaxy and limits for five DIB bands in six other H\textsubscript{i}-rich galaxies (damped Lyman-\alpha systems–DLAs). Our results reveal that H\textsubscript{i}-rich galaxies are dust poor and have significantly lower reddening than known DIB-rich Milky Way environments. We find that DIBs in H\textsubscript{i}-rich galaxies do not show the same correlation with hydrogen abundance as observed in the Milky Way; the extragalactic DIBs are underabundant by as much as 10 times. The lower limit gas-to-dust ratios of four of the H\textsubscript{i}-rich early epoch galaxies are much higher than the gas-to-dust ratios found in the Milky Way. Our results suggest that the organic molecules responsible for the DIBs are underabundant in H\textsubscript{i}-rich early epoch galaxies relative to the Milky Way.
1. Introduction

Since their discovery in 1921 (Heger 1922), the diffuse interstellar bands (DIBs) have remained the longest known interstellar absorption features without a positive identification. There have been several hundred DIBs discovered to date (Jenniskens et al. 1994; Tuairisg et al. 2000; Weselak et al. 2000). The DIBs span the visible spectrum between 4000 and 13000 Å. Despite no positive identifications, several likely organic molecular candidates have emerged as the sources of the DIBs, including polycyclic aromatic hydrocarbons (PAHs), fullerenes, long carbon chains, and polycyclic aromatic nitrogen heterocycles (PANHs) (Herbig 1995; Snow 2001; Cox & Spaans 2006a; Hudgins et al. 2005). The organic-molecular origin of the DIBs may give them an importance to astrobiology; they are now considered an important early constituent to the inventory of organic compounds on Earth (Bada & Lazcano 2002).

There are several environmental factors that are known to enhance or inhibit DIB strengths. Thus, measuring DIB strengths can give clues to the environments of galaxies like those with high neutral hydrogen (H\textsubscript{i}) content, known as damped Lyman-\alpha systems (DLAs). Measuring DIB strengths allow researchers to explore the quantities of gas, metallicity, dust, and radiation in galaxies and their influence on the strengths of the bands. Furthermore, observing DIBs in galaxies at a higher redshift, $z$, (distance or lookback time related to the expansion of the Universe) allows us to test the evolution of these organics in cosmic time.

Two important environmental factors that are often probed in galaxies are the H\textsubscript{i} content and the reddening. The H\textsubscript{i} content in DLAs is typically measured as a column density via their Lyman-\alpha line in absorption, as observed using a bright background source such as a quasar. The column density is the number of atoms of a certain element as seen along a line-of-sight projected to a unit area at the observer (typically in units of atoms cm$^{-2}$ and denoted as $N$(H\textsubscript{i}) for neutral hydrogen). The reddening is a measure of the dust content in the galactic environment. Reddening is expressed as $E(B-V)$, or the magnitude of blue light minus visible light observed relative to what is expected from typical stars or galaxies. Because dust preferentially obscures blue light, a high reddening is a signature for a high dust content. $N$(H\textsubscript{i}) is a measure of the gas phase and $E(B-V)$ is a measure of the dust phase of the ISM in galaxies.

Due to their relatively weak absorption strengths, the DIBs have been difficult to detect in extragalactic sources. Aside from the hundreds of detections within the Milky Way (Jenniskens et al. 1994; Tuairisg et al. 2000; Weselak et al. 2000), DIBs have been detected in the Magellanic Clouds (Welty et al. 2006; Cox et al. 2006b, 2007), seven starburst galaxies (Heckman & Lehnert 2000), the active galaxy Centaurus A via supernova 1986A (Rich 1987), spiral galaxy NGC 1448 via Supernovae 2001el and 2003hn (Sollerman et al. 2005), one DLA galaxy at $z = 0.524$ toward the quasar AO 0235+164 (Junkkarinen et al. 2004; York et al. 2006), and one galaxy selected by singly ionized calcium (Ca\textsc{ii}), J0013–0024, at $z = 0.157$ from the Sloan Digital Sky Survey (Ellison et al. 2007).

We further the knowledge of DIB lines in extragalactic environments by cataloguing the strengths of the $\lambda 4428$, $\lambda 5780$, $\lambda 5797$, $\lambda 6284$, and $\lambda 6613$ DIBs.
relative to the $E(B - V)$ and $(N\text{H}1)$ content of each of the seven DLAs in our sample. Observations were obtained, with seven facilities, of seven DLAs toward six QSO sightlines. The facilities and instruments used for this project are the VLT/FORS2, VLT/UVES, APO/DIS, Keck/HIRES, WHT/ISIS, and Gemini/GMOS-S.

2. Analysis & Results

There are two detections included in this work, the $\lambda 5705$ and $\lambda 5780$ DIBs first reported by [York et al., 2006], in the $z = 0.524$ DLA toward AO 0235+164. For all other DLAs in our sample, we report upper limits on the $\lambda 4428$, $\lambda 5780$, $\lambda 5797$, $\lambda 6284$, and $\lambda 6613$ DIB equivalent widths. We measured the equivalent width limits using a generalized method of the [Schneider et al., 1993] technique for finding lines and limits. We compare our measured limits to the expected DIB equivalent widths from the known Milky Way DIB–$E(B - V)$ and DIB–$(N\text{H}1)$ relations [Welty et al., 2006]. The $(N\text{H}1)$ quantities are known for the DLAs; however, [Junkkarinen et al., 2004] published the only reddening known for the DLA galaxies in our sample, AO 0235+164, with a measured $E(B - V) = 0.23$. We estimate the upper limit to the reddening using our equivalent width limits and the Milky Way DIB–$E(B - V)$ correlation. Our equivalent width limits are robust enough to constrain the upper reddening limits near the $E(B - V) < 0.04$ limit found by [Ellison et al., 2005] for the highest redshift DLA galaxies.

The results from the $(N\text{H}1)$ model suggests that the organics that give rise to the DIBs in DLAs are underabundant relative to Milky Way sightlines of the same hydrogen column density. Fig. 1 shows this by plotting the measured equivalent widths and upper equivalent width limits for the DLAs in our sample. The line is the best-fit to the Milky Way data from [Welty et al., 2006]. The Milky Way points are observed to lie within the dotted region while the Large Magellanic Cloud sightlines are observed to lie within the dashed region. The Small Magellanic Cloud sightlines are all within the dot-dashed region. The $\lambda 6284$ DIB gives the best constraints and shows that this DIB is at least 4-10 times weaker in four of our DLAs compared to what is expected in the Milky Way. As is the case for the Magellanic Clouds, the Milky Way DIB–$(N\text{H}1)$ relation does not apply to DIBs in DLAs. Many environmental factors can potentially work to inhibit the organics responsible for the DIBs so this alone can not be used as evidence that the environments of DLAs are similar to the Large or Small Magellanic Cloud. For example, the dust content, ionizing radiation, and metallicity may be quite different in DLAs relative to the Magellanic Clouds.

From our equivalent width limits we can estimate the upper limit to the reddening assuming the Milky Way DIB–$E(B - V)$ relation holds for DLAs. There are little data on DIBs in DLAs; however, [Ellison et al., 2007] create a fit to all known extragalactic points for the $\lambda 5780$ DIB. The $\lambda 5780$ DIB–$E(B - V)$ relation appears to remain valid when the extragalactic equivalent width measurements are included, although the slope is slightly steeper. Our upper limits for $E(B - V)$ yield lower limits to the gas-to-dust ratios for our DLAs; these results are shown in Fig. 2. $E(B - V)_{\text{lim}}$ are the upper limits for the reddening determined by our best equivalent width limits. The best-fit lines for the Milky Way and the Large Magellanic Cloud are given from the
Figure 1. The DIB equivalent width–\(N(\text{H}^\text{i})\) relations (Welty et al. 2006) with our DLAs added. —(a) \(\lambda 5780\) DIB. —(b) \(\lambda 5797\) DIB. —(c) \(\lambda 6284\) DIB. The solid lines are the best-fit weighted Milky Way lines. The region enclosed by the dotted lines contain the Milky Way data. The regions enclosed by the dashed lines contain the LMC data. The regions enclosed by the dot-dash lines contain the SMC data. Error bars are 1\(\sigma\), and upper limits are marked with arrows. The vertical error bars for AO 0235+164 in panel (a) are smaller than the point size and all values for this DLA are from York et al. (2006).
Figure 2. The gas-to-dust ratios of the DLAs in our sample relative to measured values in the Milky Way (MW) and the Large Magellanic Cloud (LMC). The figure is modified from Cox et al. (2006b). The plot measures the log column density \( \text{cm}^{-2} \) versus the upper limit to the log reddening for each DLA determined. The A0 0235+164 reddening measurement of 0.23±0.01 is from Junkkarinen et al. (2004). The top three lines represent the LMC while the bottom two lines represent the MW. The long-dashed LMC line gives the gas-to-dust ratio of \( 19.2 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \) from the LMC-2 data of Gordon et al. (2003). The dotted LMC line is a linear fit to the LMC data in Cox et al. (2006b) and gives a gas-to-dust ratio of \( 14.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \). The short-dashed line is the average LMC regions from (Gordon et al. 2003) and has a gas-to-dust ratio of \( 11.1 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \). The dashed MW line gives a gas-to-dust ratio of \( 4.8 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \) (Bohlin et al. 1978), and the dotted MW line is the fit to the Milky Way data from Cox et al. (2006b) which yields a ratio of \( 4.03 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \). Several of the DLAs in our sample are consistent with having higher gas-to-dust ratios than the MW and the LMC.

rich galaxies are much less suitable to create and/or sustain organic molecules. DLA galaxies do have considerably lower reddening than the Milky Way regions where DIBs are observed. Our results imply that the low reddening in DLAs will inhibit the DIBs if they are present. Reddening is dependent on dust grain sizes and abundances. It is conceivable that the organics require dust grains for their formation or are created from the same sources, such as carbon stars (Herbig 1995). A large carbon abundance may be required for the DIB–\( E(B-V) \) relations to hold true. Therefore, it is feasible that early epoch H\(_{i}\) galaxies are not conducive to the formation of the organics because they lack the necessary carbon. However, Herbig (1995) points out that the scatter in the Milky Way DIB–\( E(B-V) \) relation is real, i.e., not due to noise or systematic errors. Thus, other environmental factors such as the local ionizing radiation field and the metallicity may be important (Cox et al. 2007). Little is published about the radiation in the DLA galaxies in our sample. Their metallicities are known to be low, on the order of ~0.1 Solar metallicity, with the exception of AO 0235+164, which is metal abundant (Junkkarinen et al. 2004). Based on published work, it is not surprising that the DLA galaxy in our sample with the highest reddening
and metallicity has the only detected DIBs. Thus, the lack of dust and metals plays a large role in inhibiting the organics in our sample of early epoch H$_1$-rich galaxies; whereas, the abundance of H$_1$ is not a strong determinant in their strengths. Our DLA selection method is not representative of all early epoch galaxies; it is biased toward galaxies with low reddening. Another selection method for early epoch galaxies may be more fruitful.

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