Probing the Missing Link between the Diffuse Interstellar Bands and the Total-to-Selective Extinction Ratio $R_V$ – I. Extinction versus Reddening

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ABSTRACT

The carriers of the still (mostly) unidentified diffuse interstellar bands (DIBs) have been a long-standing mystery ever since their first discovery exactly 100 years ago. In recent years, the ubiquitous detection of a large number of DIBs in a wide range of Galactic and extragalactic environments has led to renewed interest in connecting the occurrence and properties of DIBs to the physical and chemical conditions of the interstellar clouds, with particular attention paid to whether the DIB strength is related to the shape of the interstellar extinction curve. To shed light on the nature and origin of the DIB carriers, we investigate the relation between the DIB strength and $R_V$, the total-to-selective extinction ratio, which characterizes how the extinction varies with wavelength (i.e., the shape of the extinction curve). We find that the DIB strength and $R_V$ are not related if we represent the strength of a DIB by its reddening-normalized equivalent width (EW), in contrast to the earlier finding of an anticorrelation in which the DIB strength is measured by the extinction-normalized EW. This raises a fundamental question about the appropriate normalization for the DIB EW. We argue that the hydrogen column density is a more appropriate normalization than extinction and reddening.

Key words: ISM: dust, extinction — ISM: lines and bands — ISM: molecules

1 INTRODUCTION

The enigmatic “diffuse interstellar bands” (DIBs) are a set of over 600 non-stellar absorption features observed in starlight crossing interstellar clouds, spanning the wavelength range of the near ultraviolet (UV) at $\lambda \gtrsim 4000$ Å to the near infrared (IR) at $\lambda \lesssim 1.8$ µm (e.g., see Sarre 2006). It is frustrating that, despite an extensive observational, experimental, theoretical and computational exploration of an entire century — it has been exactly 100 years since the first serendipitous detection of two DIBs (at 5780 and 5797 Å) by Mary Lea Heger, then a graduate student at Lick Observatory (see Heger 1922), although their interstellar origin was not firmly established until 15 years later by Merrill (1934).

Nevertheless, in recent years much progress has been made in detecting a large number of DIBs in a wide variety of Galactic interstellar environments, ranging from sightlines toward diffuse clouds, translucent clouds, molecular clouds, bright reflection nebulae, giant H II regions, massive star forming regions, massive young stellar clusters, and the Galactic center (see Snow & McCall 2006, Hobbs et al. 2008, 2009, Cox 2011, Cami & Cox 2014, Kres额度ski 2018, Sonnentrucker et al. 2018). The detection of DIBs in extragalactic environments has also been reported (see Cordiner 2014), ranging from the Local Group galaxies including the Large and Small Magellanic Clouds (Ehrenfreund et al. 2002; Cox et al. 2006, 2007; Welty et al. 2006; Welty et al. 2006; van Loon et al. 2013), M31 (Cordiner et al. 2008b, 2011), M33 (Cordiner et al. 2014), and others. Despite this impressive observational progress, the fundamental question of the nature and origin of the DIB carriers remains largely unresolved.
In this context, it would be of great value to explore how the DIB strength varies with $R_V \equiv A_V/E(B-V)$, the total-to-selective extinction ratio, which characterizes the steepness of the UV extinction: for lines of sight with a smaller $R_V$, the UV extinction often increases more steeply with $\lambda^{-1}$, the inverse wavelength (e.g., see Figures 4,6 of Cardelli, Clayton & Mathis 1989, hereafter CCM). On a per unit $A_V$ basis, a smaller $R_V$ implies a more severe attenuation of the UV radiation and thus a more effective protection of the DIB carriers. While this scenario is complicated by the fact that those lines of sight with a smaller $R_V$ often subject to a smaller amount of visual extinction ($A_V$), observationally, this has been demonstrated in the $\sigma$ Sco cloud toward HD 147165 (for which $R_V \approx 4.25$, Lewis et al. 2005) and the $\zeta$ Oph cloud toward HD 149757 (for which $R_V \approx 3.08$, Fitzpatrick & Massa 2007). While the interstellar reddening $[E(B-V) \approx 0.34$ for $\sigma$ Sco and $E(B-V) \approx 0.32$ for $\zeta$ Oph] is similar for these two clouds, the $5780$ Å DIB of $\sigma$ Sco is substantially stronger than that of $\zeta$ Oph. However, it is worth noting that the strengths of the $5797$ Å DIB of these very same two clouds are nearly identical (Krelowksi & Westerlund 1988). The effects of the UV starlight on the DIB strength has also been observationally studied by Cami et al. (1997) and Sonnentrucker et al. (1997) for a larger number of DIBs and a larger sample of sightlines.

To shed light on the physical and chemical nature of the still unidentified DIB carriers, we have initiated a program to explore the possible relations between the DIB strengths and the various interstellar parameters (e.g., extinction, UV radiation, and gas densities). In this work, we quantitatively examine how DIBs vary with $R_V$, first for the sightlines toward the HII region in M17 and then for a larger sample (2). It is found that the DIB strength, measured as $EW/E(B-V)$, the EW of a DIB normalized by reddening, is not correlated with $R_V$. This is in contrast to the earlier finding of an anticorrelation made by Ramírez-Tannus et al. (2018) who normalized the DIB EW by $A_V$. The results are discussed in (3) and summarized in (4).

2 IS THE DIB STRENGTH RELATED TO $R_V$?

Following Ramírez-Tannus et al. (2018), we first consider the prominent DIBs seen in M17, a giant HII region. Located in the Carina-Sagittarius spiral arm of the Galaxy at a distance of $\sim 1.98$ kpc, M17 is one of the brightest and best-studied giant HII region (Hoffmeister et al. 2008, Povich et al. 2009, Ramírez-Tannus et al. 2017). M17 is selected for this study because the sightlines toward M17 exhibit a significant spread in both extinction ($A_V \sim 3-15$ mag) and $R_V$ ($\sim 2.8-5.5$). Hanson et al. (1997) investigated the behavior of the DIBs along the sightlines toward M17, over such a wide extinction range. They found that the DIBs show little change in spectral shape. Ramírez-Tannus et al. (2018) obtained the 300–2500 nm spectra of 11 pre-main sequence OB stars with the X-shooter Spectrograph mounted on the ESO Very Large Telescope (VLT). They determined the reddening, visual extinction, and $R_V$ for the lines of sight toward these stars. They also measured the EWs of 14 prominent DIBs for most of these sightlines. As tabulated in Table (1) we adopt the reddening $E(B-V)$, $R_V$, and DIB EW data of Ramírez-Tannus et al. (2018) and examine the correlation

2 For example, DIBs were observed to be weaker by factors of $\sim 2$ or more on a per unit reddening basis in photon-dominated regions (PDR; see Jenniskens et al. 1994).

3 Also known as the “color excess”, the interstellar reddening is defined as the extinction difference between two wavebands, e.g., $E(B-V) = A_B - A_V$ is the difference between the $B$-band extinction ($A_B$) at $\lambda \approx 4400$ Å and that of the $V$-band ($A_V$) at $\lambda \approx 5500$ Å.
between the DIB EW and $R_V^{-1}$ in M17. For different lines of sight crossing different amounts of interstellar matter, the DIB EW is expected to correlate with $E(B-V)$. Therefore, to cancel out the common correlation between the DIB EW and $E(B-V)$ among the various lines of sight, we normalize the DIB EWs by $E(B-V)$. We perform a correlation analysis between the reddening-normalized EWs of 14 DIBs, $EW/E(B-V)$, and $R_V^{-1}$ for the lines of sight toward M17. As shown in Figure 3 for all 14 DIBs at 4430, 5780, 5797, 6196, 6284, 6379, 7224, 8620, 9577, 9632, 11797, 13176, and 15268 Å, the Pearson correlation coefficient $r$ never exceeds 0.50, indicating that $EW/E(B-V)$ and $R_V^{-1}$ are not correlated. This is also supported by the Kendall’s $\tau$ test (see Figure 1).

We have also performed the Pearson correlation analysis and the Kendall’s $\tau$ test for six of these 14 DIBs for a large sample of 97 sightlines of which both EWs and $R_V$ have been compiled from the literature by Xiang et al. (2017). As illustrated in Figure 2, no correlation is found between $EW/E(B-V)$ and $R_V^{-1}$.

3 DISCUSSION

Ramírez-Tannus et al. (2018) investigated the correlation between $EW/A_V$, the extinction-normalized DIB EWs, and $R_V^{-1}$ for the 14 prominent DIBs seen in M17. As reproduced here in Figure 3, it is apparent that, with the Pearson correlation coefficient $r$ exceeding 0.80 for five of the 14 DIBs and exceeding 0.60 for 10 of the 14 DIBs, $EW/A_V$ appears to correlate with $R_V^{-1}$ for the vast majority of the DIBs seen in M17. This is in stark contrast to our finding that there seems to be no correlation between $EW/E(B-V)$ and $R_V^{-1}$ (see 2).

The major difference between our approach and that of Ramírez-Tannus et al. (2018) lies in the normalization: while we normalize the DIB EW by reddening $E(B-V)$, Ramírez-Tannus et al. (2018) took the visual extinction $A_V$ as the normalization. We argue that the anticorrelation between $EW/A_V$ and $R_V^{-1}$ may be related to the fact that, for the M17 sample of Ramírez-Tannus et al. (2018), $A_V$ and $R_V$ are themselves correlated. As shown in Figure 3 of Ramírez-Tannus et al. (2018), $A_V$ and $R_V$ are themselves correlated. As shown in Figure 3, with a Pearson correlation coefficient of $r \approx -0.84$ and a Kendall’s $\tau$ correlation coefficient of $\tau \approx -0.79$ and a corresponding probability $p \approx 0.0065$ of a chance correlation, an anticorrelation between $A_V$ and $R_V^{-1}$ is apparent. Therefore, even if DIBs do not correlate with $R_V$ at all, the intrinsic anticorrelation between $A_V$ and $R_V^{-1}$ would lead to EW/$A_V$ to correlate with $R_V^{-1}$. On the other hand, as demonstrated in Figure 1, $E(B-V)$ is not related to $R_V^{-1}$.

This raises a fundamental question: when one observes the possible relations between DIBs and other interstellar parameters or among different DIBs, what is a more appropriate normalization, $A_V$ or $E(B-V)$? At first glance, $A_V$ appears to be a better normalization since $A_V$ is a direct tracer of the dust column density. However, $E(B-V)$ is a better discriminator of dust size and therefore of $R_V$ (e.g., see Figures 22.7, 22.8 of Draine 2011) in the sense that larger grains intend to be “grayer” and have larger $R_V$.

When correlating the DIB EW with $R_V$, it thus seems more appropriate to normalize the DIB EW with $E(B-V)$ rather than $A_V$. In this way, any intrinsic relation between $E(B-V)$ and $R_V$ would have been cancelled out. Also, it is well known and can be easily verified with the DIB EW data available in the public domain that the DIB strengths for most of the strong DIBs (e.g., those at 4430, 5780, 5797, 6284, 6613 Å) are more strongly correlated with $E(B-V)$ than with $A_V$. This appears to support $E(B-V)$ as a more favorable normalization than $A_V$. On the other hand, this could also be considered as evidence for supporting that DIBs actually physically anticorrelate with $R_V$, at least through the so-called “skin” or “edge” effect (Snow & Cohen 1974), i.e., in dense molecular clouds characterized by larger-than-average $R_V$ values, DIBs are weak or even completely absent at the cloud cores but grow in strength toward the cloud edges.

This is possibly caused by the accretion of the DIB carriers onto the surfaces of large dust grains under conditions which favor dust growth in dense molecular clouds. As a result, DIB carriers are relatively under-abundant and thus many DIBs exhibit smaller strengths in these environments, i.e., places where dust with larger values of $R_V$ typically reside.

We argue that neither $A_V$ nor $E(B-V)$ is an accurate tracer of the dust column density since both quantities involve the properties (e.g., size, composition) of the dust along the line of sight which exhibit regional variations. We suggest the hydrogen column density ($N_{\text{HI}}$) is a more appropriate normalization than $A_V$ and $E(B-V)$ since $N_{\text{HI}}$ directly measures the amount of interstellar material along a given sightline, while both $A_V$ and $E(B-V)$ are actually only used as proxies for $N_{\text{HI}}$. Unfortunately, in the literature there is no $N_{\text{HI}}$ information for the M17 sightlines of interest.

\[ E(B-V) = (B-V) - (B-V)_0. \] They derived $R_V$ using the relation reported in Fitzpatrick & Massa (2007): $R_V \approx -0.26 + 1.19 (A_V - A_K)/(A_B - A_V)$, where $A_K$ is the $K$-band extinction. This explains why the Pearson correlation coefficient $r$ between $A_V$ and $R_V^{-1}$ is not $-1$ which should have been the case if $R_V$ was derived directly from $A_V/E(B-V)$.

\[ \text{http://dib.uchicago.edu/public/index.html} \]

\[ \text{Indeed, Hansen et al. (1997) have already noted that the DIBs observed in the direction of M17, over the extinction range of } A_V = 3-10 \text{ mag, do not show any significant increase in strength. They suggested that either the DIB features are already saturated at a small value of } A_V, \text{ or that the interstellar material local to M17, where the increased extinction is being traced, does not contain DIB carriers.} \]
here. This prevents us from a quantitative analysis of the relation between EW/\(N_\text{H}\) and \(R_V^{-1}\).

4 SUMMARY

We have examined the relation between the DIB strength and \(R_V\) which characterizes how the extinction varies with wavelength, first for 14 DIBs in eight lines of sight toward young OB stars in the giant H\textsc{ii} region M17 and then for six of these 14 DIBs in a large sample of 97 lines of sight compiled from the literature. It is found that the DIB strength, measured as the reddening-normalized DIB EW, is not correlated with \(R_V\), in contrast to the earlier finding of an anticorrelation between the extinction-normalized DIB EW and \(R_V\). We argue that, when comparing the DIB EW with \(R_V\), neither \(A_V\) nor \(E(B-V)\) is an ideal normalization since \(A_V\) is usually intrinsically higher for regions with larger \(R_V\) (i.e., \(A_V \propto R_V\)) while \(E(B-V)\) preferably probes the surface layers of dense molecular cloud cores. We suggest that the really appropriate normalisation for the DIB EW, on physical grounds, would be \(N_\text{H}\), the hydrogen column density.

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REFERENCES

Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Boissé, P., Rollinde, E., Hily-Blant, P., et al. 2009, A&A, 501, 221
Cami, J., Sonnentrucker, P., Ehrenfreund, P., & Foing, B.H. 1997, A&A 326, 822
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 354, 245
Cami, J., & Cox, N. L. J. 2014, ed., IAU Symp. 297, The Diffuse Interstellar Bands, Cambridge Univ. Press
Campbell, E.K., Holz, M., Gerlich, D., & Maier, J.P. 2015, Nature, 523, 322
Campbell, E.K., Holz, M., & Maier, J.P. 2016, ApJL, 826, L4
Clayton, G. C. 2014, in IAU Symp. 297, The Diffuse Interstellar Bands, ed. J. Cami & N. L. J. Cox (Cambridge: Cambridge Univ. Press), 147
Cordiner, M. A. 2014, in IAU Symp. 297, The Diffuse Interstellar Bands, ed. J. Cami & N. L. J. Cox (Cambridge: Cambridge Univ. Press), 41
Cordiner, M. A., Cox, N. L. J., Trundle, R., Evans, C. J., Hunter, I., Przybilla, N., Bressolin, F., & Salama, F. 2008a, A&A, 480, 13
Cordiner, M. A., Smith, K. T., Cox, N. L. J., Evans, C. J., Hunter, I., Przybilla, N., Bressolin, F., & Sarre, P. J. 2008b, A&A, 492, L5
Cordiner, M. A., Cox, N. L. J., Evans, C. J., Trundle, C., Smith, K. T., Sarre, P. J., & Gordon, K. D. 2011, ApJ, 726, 39
Cordiner, M. A., Limmart, H., Cox, N. L. J., et al. 2019, ApJL, 875, L28
Cox, N. L. J. 2011, in IAU Symp. 280, The Molecular Universe, ed. J. Cernicharo & R. Bachiller (Cambridge: Cambridge Univ. Press), 162
Cox, N. L. J., & Spaans, M. 2006, A&A 451, 973
Cox, N. L. J., & Patat, F. 2008, A&A, 485, 9
Cox, N. L. J., Cordiner, M. A., Cami, J., et al. 2006, A&A, 447, 991
Cox, N. L. J., Boudin, N., Foing, B. H., et al. 2007, A&A, 465, 899
Cox, N. L. J., Ehrenfreund, P., Foing, B. H., et al. 2011, A&A, 531, A25
Dahlstrom, J., York, D. G., & Welty, D. E. 2013, ApJ, 773, 41
Draine, B.T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, N.J: Princeton Univ. Press)
Ehrenfreund, P., Cami, J., Jiménez-Vicente, J., et al. 2002, ApJL, 576, L117
Ellison, S. L., York, B. A., Murphy, M. T., Zych, B. J., Smith, A. M., & Sarre, P. J. 2008, MNDRS, 383, L30
Fahlman, G. G., & Walker, G. A. H. 1975, ApJ, 200, 22
Fitzpatrick, E. L., & Massa, D. 2007, ApJ, 663, 320
Foing, B.H., & Ehrenfreund, P. 1994, Nature, 369, 296
Friedman, S. D., York, D. G., McCall, B. J., et al. 2011, ApJ, 727, 33
Fulara, J., Jakobi, M., & Maier, J.P. 1993, Chem. Phys. Lett., 211, 227
Galazutdinov, G. A., Maníco, G., & Kreilowski, J. 2006, MNDRS, 366, 1075
Hanson, M. M., Howarth, I. D., & Conti, P. S. 1997, ApJ, 489, 698
Heckman, T.M., & Lehnert, M.D. 2000, ApJ, 537, 690
Heger, M. L. 1922, Lick Obs. Bull., 10, 146
Hobbs, L. M., York, D. G., Snow, T. P., et al. 2008, ApJ, 680, 1256
Hobbs, L. M., York, D. G., Thorburn, J. A., et al. 2009, ApJ, 705, 32
Hoffmeister, V. H., Chini, R., & Scheyda, C. M. 2008, ApJ, 686, 310
Jenniskens, P., Ehrenfreund, P., & Foing, B. 1994, A&A, 281, 517
Junkkarinen, V. T., Cohen, R. D., Beaver, E. A., Burbidge, E. M., Lyons, R. W., & Madejski, G. 2004, ApJ, 614, 658
Kos, J., & Zwitter, T. 2013, ApJ, 774, 72
Kreilowski, J., & Westerlund, B. E. 1988, A&A, 190, 339
Kreilowski, J. 2018, PASP, 130, 1001
Lawton, B., Churchill, C. W., York, B. A., Ellison, S. L., Snow, T. P., Johnson, R. A., Ryan, S. G., & Benn, C. R. 2008, AJ, 136, 994
Lawton, B., Churchill, C. W., York, B. A., Ellison, S. L., Snow, T. P., Johnson, R. A., Ryan, S. G., & Benn, C. R. 2008, AJ, 136, 994
Lewis, N. K., Cook, T. A., & Chakrabarti, S. 2005, ApJ, 619, 357
Merrill, P. W. 1934, PASP, 46, 227
Monreal-Ibero, A., Weilbacher, P. M., & Wendt, M. 2018, A&A, 615, 33
Monreal-Ibero, A., Weilbacher, P. M., Wendt, M., et al. 2015, A&A, 576, 3
Omont, A. 2016, A&A, 590, 52
Phillips, M. M., Simon, J. D., Morrell, N., et al. 2013, ApJ, 779, 38
Porceddu, I., Benvenuti, P., & Kreilowski, J. 1992, A&A, 260, 391
Povich, M. S., Churchwell, E., Bieging, J. H., et al. 2009, ApJ, 696, 1278
Ramírez-Tannus, M. C., Cox, N. L. J., Kaper, L., & de Koter, A. 2018, A&A, 620, A52
Ramírez-Tannus, M. C., Kaper, L., de Koter, A., et al. 2017, A&A, 604, 78
Sarre, P. J. 2006, J. Mol. Spec., 238, 1
Snow, T. P., & Cohen, J. G. 1974, ApJ, 194, 313
Snow, T. P., & McCall, B. J. 2006, ARA&A, 44, 367
Sollerman, J., Cox, N., Mattila, S., et al. 2005, A&A, 429, 559
Sonnentrucker, P. 2014, in IAU Symp. 297, The Diffuse Interstellar Bands, ed. J. Cami & N. L. J. Cox (Cambridge: Cambridge Univ. Press), 13
Sonnentrucker, P., Cami, J., Ehrenfreund, P., & Foing, B.H. 1997, A&A, 327, 1215
Sonnentrucker, P., York, B., Hobbs, L. M., et al. 2018, ApJS, 237, 40
van Loon, J. Th., Bailey, M., Tatton, B. L., et al. 2013, A&A, 550, 108
Vos, D. A. I., Cox, N. L. J., Kaper, L., Spaans, M., & Ehrenfreund, P. 2011, A&A, 533, 129
Walker, G.A.H., Bohlender, D. A., Maier, J. P., & Campbell, E. K. 2015, ApJL, 812, L8
Welty, D. E., Federman, S. R., Gredel, R., Thorburn, J. A., & Lambert, D.L. 2006, ApJS, 165, 138
Welty, D. E., Ritchey, A. M., Dahlstrom, J.A., & York, D. G. 2014, ApJ, 792, 106
Witt, A. N., Bohlin, R. C., & Stecher, T P. 1983, ApJL, 267, L47
Xiang, F. Y., Li, A., & Zhong, J. X. 2011, ApJ, 733, 91
Xiang, F. Y., Li, A., & Zhong, J. X. 2017, ApJ, 835, 107
York, B. A., Ellison, S. L., Lawton, B., Churchill, C. W., Snow, T. P., Johnson, R. A., & Ryan, S. G. 2006, ApJL, 647, L29
York, D. G., Dahlstrom, J., Welty, D. E., et al. 2014, in IAU Symp. 297, The Diffuse Interstellar Bands, ed. J. Cami & N. L. J. Cox (Cambridge: Cambridge Univ. Press), 89
Figure 1. Correlation of the reddening-normalized DIB EW with $R_{V}^{-1}$ for the lines of sight toward eight young OB stars in the giant H II region M17 for 14 DIBs at 4430 Å (a), 5780 Å (b), 5797 Å (c), 6196 Å (d), 6284 Å (e), 6379 Å (f), 6614 Å (g), 7224 Å (h), 8620 Å (i), 9577 Å (j), 9632 Å (k), 11797 Å (l), 13176 Å (m), and 15268 Å (n). Also shown is the correlation between the reddening $E(B - V)$ and $R_{V}^{-1}$ (o). Labeled in each subfigure are the Pearson correlation coefficient $r$, the Kendall’s $\tau$ coefficient and the significance level $p$. The star identifiers are also labeled in Figure 1(o).
Figure 2. Correlation of the reddening-normalized DIB EW with $R_V$ for six DIBs at 5780 Å (a), 5797 Å (b), 6196 Å (c), 6284 Å (d), 6379 Å (e), and 6614 Å (f) for a large sample of 97 sightlines of which both EWs and $R_V$ have been compiled from the literature by Xiang et al. (2017).
Figure 3. Same as Figure 1 but for EW/AV, the extinction-normalized DIB EWs. Figure 3(a) shows the correlation between AV and RV⁻¹.
Table 1. Extinction and DIB Properties in the Lines of Sight toward Eight Young OB Stars (B111, B164, B243, B253, B268, B275, B289 and B311) in M17 (Ramírez-Tannus et al. 2018).

| Extinction and DIB Properties | B111  | B164  | B243  | B253  | B268  | B275  | B289  | B311  |
|-------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| $R_V$                         | 3.86  | 4.87  | 4.64  | 4.29  | 3.47  | 3.35  | 4.80  | 4.00  |
| $A_V$/mag                     | 5.17  | 9.03  | 6.52  | 6.22  | 4.71  | 5.44  | 8.13  | 6.51  |
| $E(B-V)$/mag                  | 1.35  | 1.76  | 1.41  | 1.52  | 1.34  | 1.59  | 1.73  | 1.62  |
| EW(4430)/m˚A                  | 2027±32 | 2539±145 | 1779±240 | 2020±158 | 1742±130 | 1919±36 | 3304±311 | 2528±53 |
| EW(5780)/m˚A                  | 558±12 | 521±38 | 540±45 | 507±38 | 663±49 | 558±17 | 711±49 | 596±24 |
| EW(5797)/m˚A                  | 89±8   | 129±32 | –     | –     | 185±30 | 125±18 | –     | 168±8  |
| EW(6196)/m˚A                  | 60±6   | 62±12  | 58±13 | 51±13 | 55±13 | 64±8   | –     | 63±6   |
| EW(6284)/m˚A                  | 1691±11 | 1790±24 | 1720±34 | 1708±38 | 1580±29 | 1661±36 | 1920±57 | 1770±25 |
| EW(6379)/m˚A                  | 35±12  | 51±10  | 54±24 | 35±13 | 32±8  | 47±5   | 65±10 | 64±12  |
| EW(6614)/m˚A                  | 188±6  | 203±27 | 187±19 | 168±15 | 201±20 | 203±27 | 243±29 | 227±11 |
| EW(7224)/m˚A                  | 313±10 | 287±12 | 386±9  | 305±16 | 339±12 | 298±10 | 337±15 | 376±11 |
| EW(8620)/m˚A                  | –      | 562±17 | 485±14 | 370±12 | 493±12 | 490±12 | 457±19 | 506±5  |
| EW(9577)/m˚A                  | 371±14 | 579±11 | 479±13 | 512±20 | 435±11 | 439±10 | 526±13 | 632±17 |
| EW(9632)/m˚A                  | 401±33 | 586±26 | 499±34 | 509±47 | 531±25 | 513±27 | 550±24 | 649±27 |
| EW(11797)/m˚A                 | 278±13 | 262±14 | 306±33 | 269±29 | 336±18 | 173±44 | 255±20 | 261±14 |
| EW(13176)/m˚A                 | 923±82 | 1134±47 | 1115±108 | 1044±84 | 1016±76 | 463±70 | 928±71 | 859±53 |
| EW(15268)/m˚A                 | 395±34 | 875±25 | –      | 615±47 | 820±42 | –      | 438±18 | 401±17 |