Draft version May 15, 2017
Preprint typeset using LaTeX style emulateapj v. 05/12/14

DUST EXTINCTION TOWARDS OB STARS IN THE MOLECULAR INTERSTELLAR MEDIUM OF W3

J. L. Campbell[1,2], P. G. Martin[2], and M. Rahman[3]

Draft version May 15, 2017

ABSTRACT

While interstellar dust only accounts for $\sim 1\,\%$ of the interstellar medium (ISM) by mass, its high opacity has a substantial effect on observational measurements and often must be taken into consideration for a proper physical interpretation of astrophysical sources. The interstellar extinction curve, denoted A_λ, describes the amount of extinction in magnitudes from interstellar dust as a function of wavelength. While extinction causes objects behind dust to appear dimmer, the wavelength-dependence of A_λ is what causes attenuated sources to also appear redder, motivating the need for a 'de-reddening' correction of photometric colours and magnitudes especially in regions of high extinction. We search for an empirical relationship between dust visual extinction (A_V) and the optical depth (τ) of thermal dust such that de-reddening measurements can easily be applied directly from the τ observable which traces the amount of dust along the line of sight. Using visual and infrared photometry alongside extinction measurements of early OB stars in the W3 giant molecular cloud from the literature, we derive an upper-limit of $A_V/\tau \approx 1.75$. This is slightly less than that of the diffuse ISM which has a value of $A_V/\tau \approx 5$ and is likely a reflection of the presence of larger dust grains in the molecular ISM. To improve upon this empirical relationship, we propose a method to use the parameter space of photometric colours to select a larger sample of candidate OB stars towards which reliable extinction measurements can be made, and discuss how modelling the extinction can be used to prevent bias from intrinsically red sources in such extinction measurements.

1. INTRODUCTION

The first indication of dust in the interstellar medium (ISM) came from the observation of an apparent lack of stars in certain regions of the sky believed to be 'holes' in the universe (Herschel 1785). This was later understood to be the result of some "absorbing medium" (Barnard 1907) which was confirmed by subsequent observations and interpreted as extinction from "cosmic dust particles" (Trumpler 1930). This interstellar dust accounts for $\sim 1\%$ of the ISM by mass while the remaining $\sim 99\%$ is primarily gaseous hydrogen (H) and helium (He). Despite its low mass fraction, the presence of interstellar dust plays a crucial role in the physical and chemical evolution of the ISM, and has serious implications for observational measurements of astrophysical objects and their physical interpretation.

In dense star forming regions like molecular clouds, dust grains serve as catalysts for the chemical enrichment of the ISM; molecular species freeze-out onto their 'sticky' ice mantles, undergoing subsequent chemical reactions and sublimate back into the gas phase to enrich the ISM (Herbst & van Dishoeck 2009). Where total gas column densities are sufficient enough to achieve $N(\mathrm{HI} + \mathrm{H_2}) \gtrsim 10^3$ cm^{-3} (or ~ 1 mag of visual extinction), this process facilitates the conversion of atomic hydrogen (HI) into molecular hydrogen (H_2) (Hollenbach et al. 1971) which is the primary constituent of the gas phase ISM in molecular clouds, hence their name. In regions with sufficient column densities, H_2 can shield the ISM from ionizing ultraviolet (UV) photons (primarily originating from hot massive O stars), thereby preventing molecular disassociation and further enhancing H_2 column densities. This, along with the capability of interstellar dust to provide a cooling mechanism for the ISM, ultimately serves as a pathway for the conditions necessary for star formation.

Perhaps closer to its more common reputation among observational astronomers, interstellar dust has a significant impact on observations and often must be taken into account. This is especially true in giant molecular clouds (GMCs) where extinction affects magnitude measurements by ~ 6 mag, and has been shown to approach ~ 100 mag where the dust grains are likely more evolved (Rivera-Ingraham et al. 2015). The effect that the high opacity of interstellar dust has on magnitude measurements is not only largely controversial but imperative if accurate astrophysical interpretations are to be made. The "extinction curve", also called the "extinction law", denoted A_λ describes the amount of extinction in magnitudes from interstellar dust grains along the line of sight via scattering and absorption processes as the background starlight reaches an observer, and is the primary form in which dust extinction is studied and described. The wavelength-dependence of A_λ is what causes astrophysical objects experiencing extinction to appear not only dimmer but also redder (Cardelli et al. 1989), motivating the need for a 'de-reddening' correction in regions of high extinction to readjust photometric colours and magnitudes of attenuated sources.

The Westerhout 3 (W3) GMC is located in the Perseus spiral arm (Tieftrunk et al. 1997) at a distance of ~ 2 kpc (e.g., Hachisuka et al. 2006; Xu et al. 2006; Navarete et al. 2011) and is among the most massive star forming regions in the outer Milky Way galaxy (Rivera-Ingraham et al. 2011). As a primary site for massive star forma-

campbell@astro.utoronto.ca
[1] Department of Astronomy & Astrophysics, University of Toronto, Canada.
[2] Canadian Institute for Theoretical Astrophysics, University of Toronto, Canada.
[3] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, United States.

tion in the galaxy, W3 contains not only massive stars at varying degrees of evolution (e.g., Tieftrunk et al. 1997) but also both triggered and rare events of spontaneous star formation (e.g., Oey et al. 2005; Kerton et al. 2008). As a result, W3 is a rich environment for GMC studies and has been observed with numerous targeted studies (e.g., Elmegreen 1980; Moore et al. 2007; Ruch et al. 2007; Motte et al. 2010; Polychroni et al. 2010; Rivera-Ingraham et al. 2011, 2015). In particular, a near infrared study of W3 by Elmegreen (1980) discovered 135 stars deemed Bright Infrared Stars (BIRS) whose photometric colours were interpreted as the result of interstellar extinction primarily of massive B stars. Large all-sky surveys (Fazio et al. 2004; Skrutskie et al. 2006; Henden et al. 2009; Wright et al. 2010; Barentsen et al. 2014; Chambers et al. 2016) add a wealth of data available for investigation.

The purpose of this paper is to obtain an empirical relationship between total visual extinction (A_V) and dust optical depth (τ) towards point sources in the molecular ISM such that a calibration measure of A_V per unit dust τ can be made for de-reddening purposes. Such a calibration would be a useful form for determining the line-of-sight total extinction given a value of τ which traces the total amount of dust along the line of sight. Similar calibration measures between the gas column density and total dust extinction have been made for the diffuse ISM and translucent clouds where the gas is primarily atomic (HI) and has a typical extinction of $A_V \lesssim 2$ mag. Such studies of dense molecular regions of the ISM where extinction has typical values of ~ 6 mag, and in some regions approaches 100 mag where the dust grains have likely evolved (Rivera-Ingraham et al. 2015), is however lacking. Furthermore, HI cannot be directly measured in the molecular ISM so tracers such as CO are often employed along with assumed dust-to-gas ratios which is grounded in studies on the diffuse ISM. Recently, the τ of thermal dust in molecular clouds has become a common surrogate for gas column density measurements but the conversion from τ to $N(\mathrm{HI})$ or τ to A_V remains unknown. Such a calibration is addressed here.

The organization of this paper is as follows: Section 2 describes our target selection of stars whose extinction measurements are then modelled in Section 3. Our results and discussion are then outlined in Section 4, including our empirical derivation of A_V/τ in Subsection 4.1, and the method by which we propose to use to expand upon the stellar population in Subsection 4.2.

2. TARGET SELECTION

The spectral energy distribution function (SED) of a reddened star experiencing extinction can be written in terms of its apparent magnitude $m(\lambda)$, absolute magnitude $M(\lambda)$, and the extinction it experiences $A(\lambda)$ all as a function of wavelength as:

$$m(\lambda) = M(\lambda) + 5\log(d/10\,\mathrm{pc}) + A(\lambda), \tag{1}$$

where $m(\lambda)$ and $M(\lambda)$ are logarithmic measures of the observed and intrinsic fluxes of the star, respectively, d is the distance in parsecs, and $5\log(d/10\mathrm{pc})$ is the distance modulus (DM) (Massa & Savage 1989). Since the DM is independent of wavelength, differences in magnitudes canonically called "colours" (or "colour indices") are useful observables that eliminate the distance-dependence. The extinction curve A_λ along a single line of sight for a particular wavelength λ can therefore be determined by comparing the magnitude of a reddened star to that of an unreddened star of the same spectral type at the same distance (Aannestad & Purcell 1973). In so doing, while employing the traditional (i.e., purely historical) usage of the B (4350 Å) and V (5470 Å) magnitudes from the Johnson-Cousins UBV broadband photometric system (Johnson 1966), one obtains the following:

$$m(B-V) = M(B-V) + E(B-V). \tag{2}$$

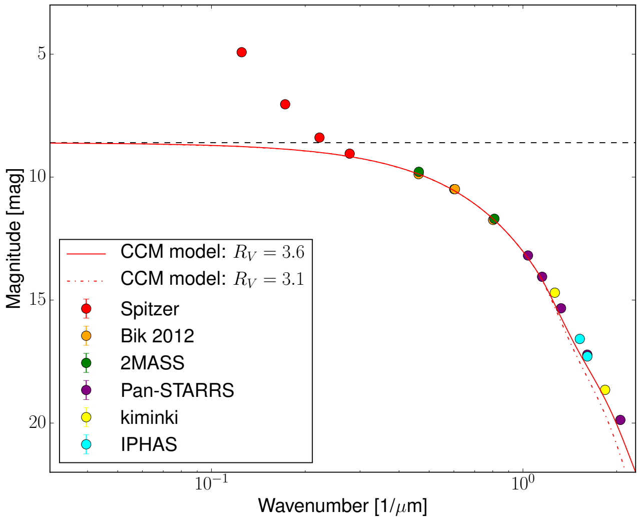
Here, we note that

$$E(B-V) = A(B) - A(V) \tag{3}$$

is referred to as the standard "colour excess" and is a measure of the *differential* (or "selective") extinction between the passbands B and V (Aannestad & Purcell 1973).

It can be seen from Equations 1 and 2 that the colour excess can simply be measured via the difference between the observed and intrinsic colours of a star where this difference arises purely from extinction; colour excess is therefore a common surrogate for differential extinction. However, a fundamental challenge with employing this method lies in obtaining the intrinsic colour of the star. Without spectroscopy to determine the colour intrinsic to the star's spectral type, there exists a degeneracy in the interpretation of red photometric colours that are inherent to the star (e.g., red giants, protostars) and those that arise purely from extinction. For example, one would be unable to definitively distinguish between a background star being highly attenuated by dust and an intrinsically red foreground star.

To navigate the challenge of determining intrinsic stellar colours with limited spectroscopic data, we target stellar populations with zero intrinsic colours such that any apparent reddening can more reliably be attributed to extinction. In the traditional Vega magnitude system where magnitudes are reported with respect to those of the A0 type star Vega, massive OB stars have negligible intrinsic colours (i.e., their SED is nearly flat in this magnitude system). We therefore study the extinction towards 14 and 91 spectroscopically-confirmed OB stars via Bik et al. (2012) and Kiminki et al. (2015), respectively, and use their placement within magnitude and colour parameter spaces to help select a larger sample of candidate OB stars for our study. In addition to derived spectral classification is supplementary JHK photometry alongside A_K extinction measurements (Bik et al. 2012) as well as those of VRI and A_V (Kiminki et al. 2015). While the observed colours of OB stars should be reliable tracers of dust extinction, we note that the presence of an infrared excess (e.g., free-free emission from the ionized disk around Be stars) and/or emission/absorption lines (e.g., photospheric Hα) can bias the observed colours and lead to an under- or over-estimate of the extinction. Efforts to minimize these biases is discussed in the following section where we model the extinction curve.



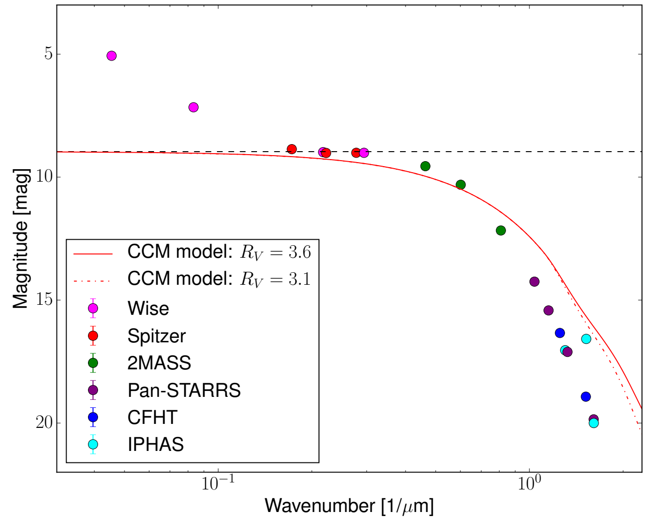


Figure 1. Spectral energy distribution functions for the Bright Infrared Stars BIRS 24 (left) and BIRS 128 (right). Shown in red are two variants of the CCM extinction model with $R_V = 3.6$ (solid) and $R_V = 3.1$ (dashed).

3. MODELLING THE EXTINCTION CURVE

Assuming spherical dust grains, the efficiency with which dust can scatter incoming light is maximized at wavelengths smaller than the grain size, decreases at wavelengths comparable to the grain size, and becomes negligible at wavelengths longer than the grain size (Mie 1908; Debye 1909). It is perhaps unsurprising then that extinction was originally believed to follow a linear relationship with frequency such that it is strongest at short wavelengths (e.g., optical and UV) and weakest at long wavelengths (e.g., infrared and radio). While this general trend is true of extinction and does in fact apply to the visual regime, subsequent studies have shown that the extinction curve exhibits a much more elaborate characteristic shape with power-law regions and other complex features such as ‘knees’ and ‘bumps’ (Aannestad & Purcell 1973). In addition to the observed intricacy of the general shape of the extinction curve, it has been shown that the aforementioned features are sensitive to both the grain size distribution and the grain chemical composition (Massa & Savage 1989). While this implies that A_λ can be a useful diagnostic to study the physical and chemical nature of interstellar dust grains, the sensitivity of extinction on the local environment results in an extinction curve that varies across different lines of sight, increasing the difficulty in determining the de-reddening correction required due to interstellar extinction.

To translate the differential extinction seen in Equation 3 into a measure of the absolute (i.e., total) extinction, one needs to know the shape of the extinction curve. Cardelli et al. (1989) found that the entire shape of the extinction curve could be parameterized by a single variable R_V referred to as the ratio of total-to-selective extinction and defined as:

$$R_V = \frac{A_V}{E(B-V)} = \frac{A_V}{A_B - A_V} \qquad (4)$$

(hereafter referred to as the CCM model). Not only is R_V an incredibly useful tool for translating differential to total extinction, but it does so with what is most readily measured: colour excess. While it has been shown that the R_V galactic average is 3.1 (Draine 2003) where the ISM is primarily atomic, we adopt a value of 3.6 which has been shown to better represent the extinction in W3 (Kiminki et al. 2015) where the ISM is primarily molecular. The destruction or removal of small dust grains from the radiation field of massive stars could cause a higher than average R_V characteristic of larger dust grains (Hollenbach et al. 1971; Kiminki et al. 2015).

Figure 1 shows the SEDs for BIRS 24 (left) and BIRS 128 (right) with two variants of the CCM extinction model: $R_V = 3.1$ (the galactic average) and $R_V = 3.6$ (adopted in this paper). Assuming no extinction, the SED of an OB star is expected to be approximately flat such that deviations below the horizontal dashed line is a direct measure of extinction in magnitudes. BIRS 24 was targeted in both spectroscopic studies of Bik et al. (2012) and Kiminki et al. (2015) with a derived spectral classification of B0.5-B2V. As an early-type main sequence B star, it can be seen that the SED is well modelled by the CCM extinction curve for $\geq 50\ \mu\text{m}^{-1}$. In this regime of the SED, the model slightly overestimates the extinction which is likely a result of the fact that the intrinsic colours of OB stars are not exactly zero and that the extinction should not be measured from a perfectly flat line. For $\leq 50\ \mu\text{m}^{-1}$, this particular source exhibits an infrared excess, possibly from free-free emission in an ionized circumstellar disk which cannot be modelled with extinction alone. BIRS 128 on the other hand was not targeted by these spectroscopic studies so we used our infrared CFHT spectra to determine its spectral classification. In contrast to the early type source, BIRS 128 is a late type M2II supergiant and is not well modelled by either of the CCM extinction models anywhere along its SED. These two extreme cases support the notion that early type OB stars should be reliable tracers of extinction. In addition to this, extinction models can not only be a useful tool to locate features such as infrared excesses but can also be used to identify intrinsically red (super)giants, both of which would bias extinction measurements.

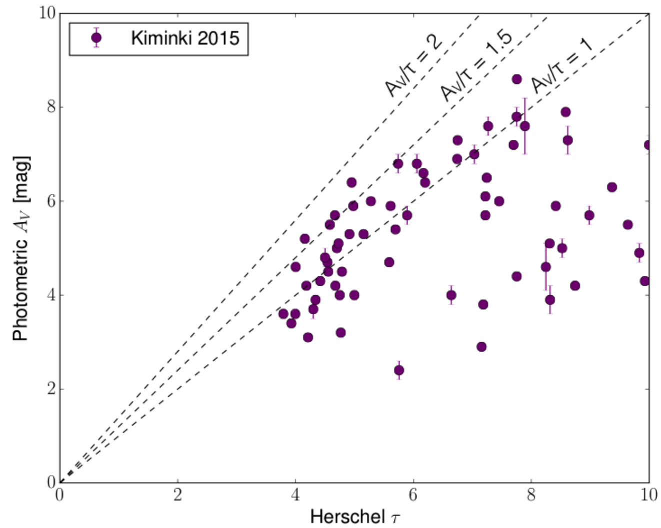


Figure 2. Photometric visual extinction A_V as a function of Herschel thermal dust optical depth τ towards the spectroscopically-confirmed OB stars via Kiminki et al. (2015).

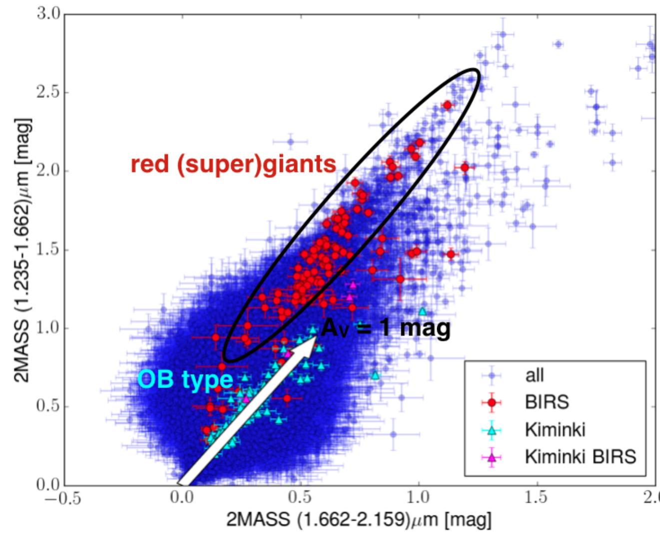


Figure 3. A 2MASS colour-colour diagram of $J - H$ versus $H - K$ for all sources in W3. The cyan triangles represent the spectroscopically-confirmed OB stars (Bik et al. 2012; Kiminki et al. 2015), the red circles represent the BIRS, and the magenta triangles represent the small number of BIRS which have been spectroscopically confirmed as OB stars. The white arrow shows the reddening vector for $A_V = 1$ mag along which the OB stars move with increasing dust extinction while the black ellipse indicates the location of red (super)giants.

4. RESULTS AND DISCUSSION

4.1. *Ratio of Dust Optical Depth to Colour Excess*

To perform our calibration measurement, we obtained dust τ towards each of the spectroscopically-confirmed OB stars in W3 (Bik et al. 2012; Kiminki et al. 2015) using *Herschel* thermal dust optical depth maps. A cubic spline interpolation was applied to the Herschel map to determine τ for the reported stellar positions which were then compared with the extinction measurements. To translate A_K to A_V, we assumed an extinction law following Cardelli et al. (1989) with $R_V = 3.6$ such that $A_K = 0.12\ A_V$.

Figure 2 shows our results of photometrically-derived A_V versus dust τ where the dashed lines have slopes of 1, 1.5, and 2. For any measurement made towards the sightline of a star within W3, A_V will approach a maximum when the star is towards the far end of the cloud where it is behind all of the dust and will approach a minimum where the star is near the foreground and only experiencing extinction from the intergalactic medium (IGM). Since thermal dust τ traces all of the dust along the line of sight, we thus search for an upper envelope of A_V versus τ which more closely resembles the true relationship. As can be seen in Figure 2, we find an upper envelope relation of $A_V \approx 1.75\tau$. Dust τ maps of the IGM could be used to remove the foreground contribution which would more accurately resemble A_V strictly from dust within W3.

In a survey of the diffuse ISM in the galactic plane composed primarily of neutral hydrogen, Bohlin et al. (1978) measured an average ratio of total hydrogen column density to colour excess of

$$< N(\mathrm{H}I) + N(\mathrm{H}_2) > /\ E(B-V) = 5.8 \times 10^{21}\,\mathrm{cm}^{-2}\,\mathrm{mag}^{-1}.$$

which translates to $A_V \approx 5\tau$ and is very close to our measurement. The fact that we measure a slightly lower extinction per unit dust optical depth is likely the result of the fact that the molecular ISM is comprised of larger dust grains (Hollenbach et al. 1971; Kiminki et al. 2015). Increasing the stellar population towards which extinction measurements can be used would increase the probability of approaching the upper-envelope of this relationship; such a method is described in the following section.

4.2. *Expanding the OB Stellar Population*

To expand upon the target list of OB stars to populate Figure 2 with a larger sample, a rich collection of photometry was utilized to cover passbands from the optical to far infrared: WISE, IRAC/Spitzer, 2MASS, IPHAS, CFHT, and Pan-STARRS. For every photometric data set, all canonical colour-magnitude diagrams (CMDs) and colour-diagrams (CCDs) were analyzed to search for the optimal parameter space within which early type OB stars from the surveys of Bik et al. (2012) and Kiminki et al. (2015) were strongly separated from intrinsically red astrophysical sources. This procedure entailed locating both IRAC and Hershel derived protostars (Class 0, 0/I, and II) as well as background galaxies in addition to the OB stars for each of these diagrams.

Following Bik et al. (2012), Figure 3 is an example of a CCD showing $J - H$ versus $H - K$ colours via 2MASS photometry for all sources in W3. The cyan triangles display the OB stars via Kiminki et al. (2015) and the white arrow shows the reddening vector for $A_V = 1$ mag. For an object with approximately zero intrinsic colours such as OB stars, the reddening vector describes the trajectory along which attenuated objects move in this colour-colour space with increasing extinction beginning at the origin. It can be seen that all of the OB stars lie along the reddening vector implying that their observed colours are in fact due to extinction; the two that lie significantly below the reddening vector are potential YSOs as they have unusually red $H - K$ colours (Bik et al. 2012). In addition to these are BIRS which were originally interpreted as primarily reddened OB stars experiencing dust extinction (Elmegreen 1980), however our CFHT spectroscopy has indicated several of these to be red giants and supergiants which all lie in the circle area indicated. This suggests that this particular CCD can be used to select a larger sample of OB stars which lie along the reddening vector without being too biased from intrinsically red astrophysical sources. As discussed in Section 3, modelling the extinction curve of such a population of stars could serve as an additional constraint to remove such biases.

While the 2MASS $J-H$ versus $H-K$ CCD shown in Figure 3 could be used to expand our sample of candidate OB stars, modelling the extinction suggests that photometric colours from more widely separated passbands could more effectively separate OB stars from red (super)giants. As shown in the bottom of Figure 1, the passbands at higher frequencies (e.g., the *grizy* passbands from Pan-STARRS) have magnitude measurements which deviate more from the extinction model than the 2MASS *JHK* magnitudes do. This suggests that using a CCD with some combination of e.g., 2MASS and Pan-STARRS photometry, such as $J-K$ versus $i-z$, could provide the tools to more accurately locate the early type OB stars. Increasing the sample of OB stars for this study would improve the probability of extinction measurements being made towards stars near the far end of W3 such that A_V traces more of the dust and the upper-envelope in Figure 2 could be more accurately determined.

5. ACKNOWLEDGMENTS

Special thanks to Dustin Lang who provided valuable assistance with `Astrometry.net` as well as Chris Sasaki who provided digital copies of the original BIRS photographic plates (Elmegreen 1980).

The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation Grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.

This paper makes use of data obtained as part of the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS, www.iphas.org) carried out at the Isaac Newton Telescope (INT). The INT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. All IPHAS data are processed by the Cambridge Astronomical Survey Unit, at the Institute of Astronomy in Cambridge. The bandmerged DR2 catalogue was assembled at the Centre for Astrophysics Research, University of Hertfordshire, supported by STFC grant ST/J001333/1.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

This research has made use of the NASA/ IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

This research was made possible through the use of the AAVSO Photometric All-Sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund.

REFERENCES

Aannestad, P. A., & Purcell, E. M. 1973, Interstellar Grains, ARA&A, 11, 309 2, 2, 3

Barentsen, G., Farnhill, H. J., Drew, J. E., et al. 2014, The second data release of the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS DR2), MNRAS, 444, 3230 1

Barnard, E. E. 1907, On a nebulous groundwork in the constellation Taurus., ApJ, 25, doi:10.1086/141434 1

Bendo, G. J., Baes, M., Bianchi, S., et al. 2014, The identification of dust heating mechanisms in nearby galaxies using Herschel 160/250 and 250/350 micron surface brightness ratios, ArXiv e-prints, arXiv:1409.1815

Bertin, E., & Arnouts, S. 1996, SExtractor: Software for source extraction., A&AS, 117, 393

Bik, A., Henning, T., Stolte, A., et al. 2012, Age Spread in W3 Main: Large Binocular Telescope/LUCI Near-infrared Spectroscopy of the Massive Stellar Content, ApJ, 744, 87 2, 3, 4.1, 3, 4.2

Bik, A., Stolte, A., Gennaro, M., et al. 2014, Deep near-infrared imaging of W3 Main: constraints on stellar cluster formation, A&A, 561, A12

Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, A survey of interstellar H I from L-alpha absorption measurements. II, ApJ, 224, 132 4.1

Cardelli, J. A. 1988, Total-to-selective extinction and the formation of molecules in diffuse interstellar clouds, ApJ, 335, 177

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, The relationship between infrared, optical, and ultraviolet extinction, ApJ, 345, 245 1, 3, 4.1

Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, The Pan-STARRS1 Surveys, ArXiv e-prints, arXiv:1612.05560 1

Chapin, E. L., Berry, D. S., Gibb, A. G., et al. 2013, SCUBA-2: iterative map-making with the Sub-Millimetre User Reduction Facility, MNRAS, 430, 2545

de Wit, W. J., Testi, L., Palla, F., & Zinnecker, H. 2005, The origin of massive O-type field stars: II. Field O stars as runaways, A&A, 437, 247

Debye, P. 1909, Der Lichtdruck auf Kugeln von beliebigem Material, Annalen der Physik, 335, 57 3

Dempsey, J. T., Friberg, P., Jenness, T., et al. 2013, SCUBA-2: on-sky calibration using submillimetre standard sources, MNRAS, 430, 2534

Draine, B. 2003, Interstellar Dust Grains, Annual Review of Astronomy and Astrophysics, 41, 241 3

Draine, B. T., & Li, A. 2007, Infrared Emission from Interstellar Dust. IV. The Silicate-Graphite-PAH Model in the Post-Spitzer Era, ApJ, 657, 810

Drew, J. E., Greimel, R., Irwin, M. J., et al. 2005, The INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS), MNRAS, 362, 753

Elmegreen, D. M. 1980, Star formation in W3 and W4 - Discovery of 135 possibly embedded near-infrared stars, ApJ, 240, 846 1, 4.2, 5

Fazio, G. G., Hora, J. L., Allen, L. E., et al. 2004, The Infrared Array Camera (IRAC) for the Spitzer Space Telescope, ApJS, 154, 10 1

Feigelson, E. D., & Townsley, L. K. 2008, The Diverse Stellar Populations of the W3 Star-forming Complex, ApJ, 673, 354

Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, The Herschel-SPIRE instrument and its in-flight performance, A&A, 518, L3

Hachisuka, K., Brunthaler, A., Menten, K. M., et al. 2006, Water Maser Motions in W3(OH) and a Determination of Its Distance, ApJ, 645, 337 1

Henden, A. A., Welch, D. L., Terrell, D., & Levine, S. E. 2009, in American Astronomical Society Meeting Abstracts, Vol. 214, American Astronomical Society Meeting Abstracts #214, 669 1

Herbst, E., & van Dishoeck, E. F. 2009, Complex Organic Interstellar Molecules, Annual Review of Astronomy and Astrophysics, 47, 427 1

Herschel, W. 1785, On the Construction of the Heavens., Philosophical Transactions of the Royal Society of London Series I, 75, 213 1

Heyer, M. H., & Terebey, S. 1998, The Anatomy of the Perseus Spiral Arm: ^{12}CO and IRAS Imaging Observations of the W3-W4-W5 Cloud Complex, ApJ, 502, 265

Hill, T., Motte, F., Bontemps, S., et al. 2010, in SF2A-2010: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, ed. S. Boissier, M. Heydari-Malayeri, R. Samadi, & D. Valls-Gabaud, 225

Holland, W. S., Bintley, D., Chapin, E. L., et al. 2013, SCUBA-2: the 10 000 pixel bolometer camera on the James Clerk Maxwell Telescope, MNRAS, 430, 2513

Hollenbach, D. J., Werner, M. W., & Salpeter, E. E. 1971, Molecular Hydrogen in H i Regions, ApJ, 163, 165 1, 3, 4.1

Johnson, H. L. 1966, Astronomical Measurements in the Infrared, ARA&A, 4, 193 2

Kerton, C. R., Arvidsson, K., Knee, L. B. G., & Brunt, C. 2008, Sequential and spontaneous star formation around the mid-infrared halo HII region KR 140, MNRAS, 385, 995 1

Kerton, C. R., Martin, P. G., Johnstone, D., & Ballantyne, D. R. 2001, A Submillimeter View of Star Formation near the H II Region KR 140, ApJ, 552, 601

Kiminki, M. M., Kim, J. S., Bagley, M. B., Sherry, W. H., & Rieke, G. H. 2015, The O- and B-Type Stellar Population in W3: Beyond the High-Density Layer, ApJ, 813, 42 2, 3, 2, 4.1, 4.1, 3, 4.2

Lada, C. J., & Lada, E. A. 2003, Embedded Clusters in Molecular Clouds, ARA&A, 41, 57

Lee, T. A. 1968, Interstellar extinction in the Orion association, ApJ, 152, 913

Linz, H., Henning, T., Feldt, M., et al. 2009, Mid-infrared interferometry of massive young stellar objects. I. VLTI and Subaru observations of the enigmatic object M8E-IR, A&A, 505, 655

Maciel, W. J. 2013, Astrophysics of the Interstellar Medium ("Springer-Verlag New York"), doi:10.1007/978-1-4614-3767-3

Massa, D., & Savage, B. 1989, in IAU Symposium, Vol. 135, Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens, 3 2, 3

Men'shchikov, A., André, P., Didelon, P., et al. 2012, A multi-scale, multi-wavelength source extraction method: getsources, A&A, 542, A81

Mie, G. 1908, Beitrge zur Optik trber Medien, speziell kolloidaler Metallsungen, Annalen der Physik, 330, 377 3

Moore, T. J. T., Bretherton, D. E., Fujiyoshi, T., et al. 2007, The star-forming content of the W3 giant molecular cloud, MNRAS, 379, 663 1

Morino, J.-I., Yamashita, T., Hasegawa, T., & Nakano, T. 1998, Reflected infrared spectrum of a massive protostar in Orion, Nature, 393, 340

Motte, F., Zavagno, A., Bontemps, S., et al. 2010, Initial highlights of the HOBYS key program, the Herschel imaging survey of OB young stellar objects, A&A, 518, L77 1

Myers, P. C. 1985, in Protostars and Planets II, ed. D. C. Black & M. S. Matthews, 81–103

Navarete, F., Figueredo, E., Damineli, A., et al. 2011, The Stellar Content of Obscured Galactic Giant H II Regions. VII. W3, AJ, 142, 67 1

Nguyen Luong, Q., Motte, F., Hennemann, M., et al. 2011, The Herschel view of massive star formation in G035.39-00.33: dense and cold filament of W48 undergoing a mini-starburst, A&A, 535, A76

Oey, M. S., Watson, A. M., Kern, K., & Walth, G. L. 2005, Hierarchical Triggering of Star Formation by Superbubbles in W3/W4, AJ, 129, 393 1

Ojha, D. K., Tamura, M., Nakajima, Y., et al. 2004, Deep Near-Infrared Observations of the W3 Main Star-forming Region, ApJ, 608, 797

Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, Herschel Space Observatory. An ESA facility for far-infrared and submillimetre astronomy, A&A, 518, L1

Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, The Photodetector Array Camera and Spectrometer (PACS) on the Herschel Space Observatory, A&A, 518, L2

Polychroni, D., Moore, T. J. T., & Allsopp, J. 2010, in Astronomical Society of the Pacific Conference Series, Vol. 424, 9th International Conference of the Hellenic Astronomical Society, ed. K. Tsinganos, D. Hatzidimitriou, & T. Matsakos, 165 1

Preibisch, T., Roccatagliata, V., Gaczkowski, B., & Ratzka, T. 2012, Herschel far-infrared observations of the Carina Nebula complex. I. Introduction and global cloud structure, A&A, 541, A132

Rachford, B. L., Snow, T. P., Destree, J. D., et al. 2009, Molecular Hydrogen in the Far Ultraviolet Spectroscopic Explorer Translucent Lines of Sight: The Full Sample, ApJS, 180, 125

Rieke, G. H., & Lebofsky, M. J. 1985, The interstellar extinction law from 1 to 13 microns, ApJ, 288, 618

Rivera-Ingraham, A., Martin, P. G., Polychroni, D., & Moore, T. J. T. 2011, Star Formation and Young Stellar Content in the W3 Giant Molecular Cloud, ApJ, 743, 39 1

Rivera-Ingraham, A., Martin, P. G., Polychroni, D., et al. 2013, Herschel Observations of the W3 GMC: Clues to the Formation of Clusters of High-mass Stars, ApJ, 766, 85

—. 2015, Herschel Observations of the W3 GMC (II): Clues to the Formation of Clusters of High-mass Stars, ApJ, 809, 81 1

Ruch, G. T., Jones, T. J., Woodward, C. E., et al. 2007, Spitzer Observations of the Giant Molecular Cloud W3, ApJ, 654, 338 1

Savage, B. D., & Jenkins, E. B. 1972, A Survey of Local Interstellar Hydrogen from OAO-2 Observations of Lyman Alpha Absorption., ApJ, 172, 491

Savage, B. D., & Mathis, J. S. 1979, Observed properties of interstellar dust, ARA&A, 17, 73

Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, The Two Micron All Sky Survey (2MASS), AJ, 131, 1163 1

Tieftrunk, A. R., Gaume, R. A., Claussen, M. J., Wilson, T. L., & Johnston, K. J. 1997, The H II/molecular cloud complex W3 revisited: imaging the radio continuum sources using multi-configuration, multi-frequency observations with the VLA., A&A, 318, 931 1

Tielens, A. G. G. M. 2013, The molecular universe, Reviews of Modern Physics, 85, 1021

Trumpler, R. J. 1930, Absorption of Light in the Galactic System, PASP, 42, 214 1

White, G. J., Nelson, R. P., Holland, W. S., et al. 1999, The Eagle Nebula's fingers - pointers to the earliest stages of star formation?, A&A, 342, 233

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, The Wide-field Infrared Survey Explorer (WISE): Mission Description and Initial On-orbit Performance, AJ, 140, 1868 1

Wynn-Williams, C. G. 1977, in IAU Symposium, Vol. 75, Star Formation, ed. T. de Jong & A. Maeder, 105–118

Xu, Y., Reid, M. J., Zheng, X. W., & Menten, K. M. 2006, The Distance to the Perseus Spiral Arm in the Milky Way, Science, 311, 54 1