STRUCTURE GENERATION: WHAT CAN GLIMPSE TEACH US ABOUT THE ISM STRUCTURE?

FABIAN HEITSCH\textsuperscript{1,2}, BARBARA A. WHITNEY\textsuperscript{3}, REMY INDEBETOUW\textsuperscript{4}, MARILYN R. MEADE\textsuperscript{5}, BRIAN L. BABLER\textsuperscript{5}, AND ED CHURCHWELL\textsuperscript{5}

ABSTRACT

Diffuse emission in the mid-infrared shows a wealth of structure, that lends itself to high-resolution structure analysis of the interstellar gas. A large part of the emission comes from polycyclic aromatic hydrocarbons, excited by nearby ultra-violet sources. Can the observed diffuse emission structure be interpreted as column density structure? We discuss this question with the help of a set of model molecular clouds bathed in the radiation field of a nearby O-star. The correlation strength between column density and “observed” flux density strongly depends on the absolute volume density range in the region. Shadowing and irradiation effects may completely alter the appearance of an object. Irradiation introduces additional small-scale structure and it can generate structures resembling shells around HII-regions in objects that do not possess any shell-like structures whatsoever. Nevertheless, structural information about the underlying interstellar medium can be retrieved. In the more diffuse regime ($n$(HI) $\lesssim$ 100 cm$^{-3}$), flux density maps may be used to trace the 3D density structure of the cloud via density gradients. Thus, while caution definitely is in order, mid-infrared surveys such as GLIMPSE will provide quantitative insight into the turbulent structure of the interstellar medium.

Subject headings: radiative transfer — turbulence — methods:numerical — ISM:dust,extinction — ISM:structure — infrared:ISM

1. THE PROBLEM

Diffuse emission in the infrared seems like a perfect laboratory to study the dynamics of the interstellar medium. Recent large-scale surveys by the Spitzer Space Telescope, specifically the GLIMPSE project\textsuperscript{1} (Benjamin et al. 2003), have provided us with unprecedented high-resolution data of the diffuse emission in the mid-infrared (MIR). At first glance the wealth of structure exhibited in the flux density maps seems a striking argument by itself for structure analysis.

However, the conspicuous structures themselves – namely shells, bubbles, filaments and dark clouds (see e.g. Churchwell et al. 2004, 2006, Heitsch et al. 2006, Jackson et al. 2006, Mercer et al. 2006) raise the question of how much of the observed structure actually corresponds to physical structure. Flux density maps contain information about volume density, column density and excitation, but to extract one of them is only possible under assumptions. For the structure analysis, ideally, we are interested in volume density, which is accessible only indirectly, leaving us with column density as a second best at most. In fact, over a broad range of wavelengths from ultraviolet to infrared, the opportunities seem to be rather rare where we can interpret observed intensity maps of diffuse emission as information about the underlying column density structure. More often than not the medium is optically thick for the emitted radiation, or denser components of the ISM act as absorbers.

Optical depth effects become weaker with increasing wavelength, which is why the mid-IR ( $\sim$ 5µm) takes a somewhat special position (for a study of correlation between emission and column density in the far-IR see e.g. Bethell et al. 2004 and Schnee et al. 2000). At longer wavelengths from the far-IR through millimeter, current observatories have rather poor spatial resolution, precluding study of small-scale interstellar structure. With a dust/PAH extinction cross section of $C_{ext} \approx 10^{-23}$ cm$^2$ per H-atom (Draine 2003; Li & Draine 2001a,b), the optical depth for MIR emission in molecular clouds should range below or around 1, which would encourage a direct interpretation of flux density as column density. For the near-infrared (NIR) this possibility has been discussed and supported by Padoan et al. (2000) to interpret so-called “cloudshine” observations by Foster & Goodman (2000), although there, the column densities would have to be substantially smaller than in the MIR.

Although applicable to a wider range of surveys, this paper focuses on the MIR diffuse emission as seen by the IRAC camera of the Spitzer Space Telescope. To a large extent, the emission in the [5.8] and [8.0] bands comes from polycyclic aromatic hydrocarbons (PAHs) (to a lesser extent they also contribute to the [3.6] band, Draine 2003), mostly excited in the environment of nearby UV sources.

Two (not unrelated) issues are raised in the MIR: (1) The medium is generally optically thick for the soft UV-radiation longward of 912Å that excites the PAH emission. Thus, only the outer layers of any structures – unless really diffuse – are excited and thereby traced out in the MIR, giving the object a filamentary appearance. (2) Observationally, there seems to be a strong morphological bias to shells in the PAH-emission. These could be dynamical shells (see e.g. Churchwell et al. 2006),...
like e.g. windblown bubbles or HII regions. However, the destruction of PAHs around the UV source could also lead to a shell-like structure. And finally, these shells could be irradiation effects as noted under (1).

And, of course, a combination of mechanisms is possible also. Moreover, the usual projection problem introduces a bias to interpreting objects as being two-dimensional, while they could be very “3D”: More diffuse material gets ionized or blown away first, leaving the ubiquitous elephant trunk remnant structures (for an impressive example of this problem see the GLIMPSE study of RCW49, Churchill et al. [2004]).

We investigate the appearance of a model molecular cloud in the radiation field of a nearby UV-source, in order to quantify the correspondence of various measures and tracers between the original column density maps and the derived flux density maps. Rescaling the density range in the models allows us to mimic different physical environments, from diffuse clouds to dense molecular clouds and cores. The appearance of the original cloud can be completely altered by irradiation. Only for densities of up to \( n(\text{HI}) \approx 100 \text{ cm}^{-3} \) can the flux density actually be interpreted as column density. Above that, MIR self-extinction and strong shadowing effects in the UV will let the maps diverge. However, even for the highest density range (up to \( n(\text{HI}) = 10^5 \text{ cm}^{-3} \)), where the flux density maps bear no resemblance to the column density, the structural properties of the original column density distribution still can be retrieved from the flux density.

Our results demonstrate that the diffuse emission data as made available by GLIMPSE can serve as a powerful means to analyze the (dynamical) structure of the interstellar medium. This study aims at pointing out possible pitfalls and at giving a rule-of-thumb estimate where flux density structure could be trusted to represent column density. In the next section \( \S 2 \), we will give some observational motivation in the form of diffuse emission maps from the GLIMPSE data. We are deferring the full structure analysis of the GLIMPSE data to a future paper. The models and the details of the radiative transfer treatment are described in \( \S 3 \). The results (\( \S 4 \)) are summarized in \( \S 5 \).

2. Observational Motivation

The following maps are extracted from images of the GLIMPSE project. The data were processed through the GLIMPSE pipeline reduction system (Benjamin et al. 2003; Whitney et al. 2004). Point sources were extracted from each frame using a modified version of DAOPHOT (Stetson 1987), and the individual residual (i.e. without point sources) frames produced by DAOPHOT were mosaicked. Only sources fit well by a stellar point-spread-function (PSF) were extracted. Thus saturated and near-saturated stars remain in the images. In addition, there are some artifacts resulting from point-source subtractions due to the undersampling of the stellar PSF at IRAC wavelengths. Figures 1-5 show \([8.0]\) residual mosaic images displayed in Galactic coordinates. We will split the maps into three categories: volume illumination (\( \S 2.1 \)), absorption and shadowing (\( \S 2.2 \)), and high-density environments (\( \S 2.3 \)).

2.1. Volume Illumination: optically thin in the UV

Fig. 1.— Residual image of diffuse emission at \([8.0]\) micron, centered on \((l,b) = (51.8, +0.6)\).

Fig. 2.— Residual image of diffuse emission at \([8.0]\) micron, centered on \((l,b) = (343.5, -0.3)\).

Figures 1 and 2 show two examples of “volume-filling” diffuse emission, i.e. the optical-depth effect described in \( \S 1 \) does not seem to be the dominant structure generation mechanism. Rather, it seems, the diffuse emission traces the volume density. While Figure 1 shows a clear shell-like structure, Figure 2 exhibits dark filaments, probably extinction in the MIR against a bright diffuse background. The volume illumination could either stem from material that is optically thin for the exciting UV provided by a nearby star or by the interstellar radiation field (Fig. 2), or arise in an environment which – although at higher densities – contains several UV-sources, so that we still see large parts of the volume in PAH-emission (Fig. 1).

2.2. Dark Clouds: Absorption and Shadowing

Figures 3 and 4 give two examples of structures that are typical of the GLIMPSE data: the combination of
bright and dark features in one and the same object.

In Figure 8, the (Galactic) North side of the filament is seen in emission, while the South side shows dark structures. Figure 4 displays a structure composed of bright vertical filaments, which may be an example of volume illumination (see previous section), while the object in question is located at smaller longitudes \( l \) than the filament, at \((l, b) = (309.04, -0.42)\): the left side is emitting, while the right side is seen as dark structure. In contrast, the top of the same Figure shows a “pure” dark cloud, without any irradiation features. The reader will find more examples in the other frames. This raises the question of whether we see two physically distinct classes of objects here, or whether the “bright-dark” clouds are just an illuminated version of the classic dark clouds. The “bright-dark” clouds can often be associated with irradiating sources (see [Heitsch et al. 2006a]), so that we will identify the two morphological classes as one and the same type of object, namely dark clouds.

2.3. High-density Environments

The region around \((l, b) = (30.7, 0.0)\) (Fig. 8) shows one of the many bubbles in the GLIMPSE data (Churchwell et al. 2006). Bright dust/PAH emission and dark clouds form an intricately structured network. The Northern part of the bubble exhibits several shell-like structures, whose brightness tapers off to the diffuse background more or less immediately. The region is compact and contains a lot of dark extinction regions in the bright emission regions, indicating that this is a high-density environment. Note, however, that darker regions in emission could also just mean that the PAHs have been destroyed around the UV source. Volume illumination seems to play less of a role here, instead, the rim effects mentioned in the introduction seem to have come into full play.

3. Irradiation of a Model Cloud
3.1. The Simulations

We employed two model series: Series A is meant to resemble star formation regions in the Galactic disk. It is derived from cloud dispersal models in a turbulent flow (Heitsch et al. 2006a), and corresponds to a box length of 44 pc, a background density of 0.5 cm\(^{-3}\), and a cloud density of 150 cm\(^{-3}\). Model A is in approximate pressure equilibrium, with a temperature of 9500 K in the ambient medium. The model is not self-gravitating.

Series B stems from self-gravitating MHD-turbulence models in a periodic box (Heitsch et al. 2001a, b). It is intended to be typical for conditions within a molecular cloud, with a box size of \( \approx 3 \) pc and a mean density of 1000 cm\(^{-3}\), an (isothermal) temperature of 10 K and a turbulent rms velocity of 1 km s\(^{-1}\). As we will see below, self-gravitation has already lead to core formation.

Both model series A and B have a resolution of 256\(^3\) grid cells. The density contrast can be adapted to test irradiation effects in various environments.

3.2. UV Source and Ray Tracing

The UV-source is assumed to be a O5V star that can be placed anywhere in the simulation domain. Note that we are just investigating the radiation paths of the stellar UV-photon. The models do not account for ionization or stellar winds, and thus cannot provide us with estimates how they would affect the emission structure. We further assume that only UV-photons with \( \lambda > 912\) \( \AA \) are available for PAH-excitation, and that photons with shorter wavelength have already been absorbed within the HII region around the star. We follow the photons on rays through the simulation domain. The discretization in longitude and latitude follows the HealPix prescription (Górski et al. 2005) in order to guarantee equal areas for each ray. Rays are traced within a tree-structure such that optical depths are known locally at each node of the tree. The number of rays is determined by the number of cells on a sphere with radius \( r \) (in grid cells) as \( N_{\text{ray}} = 4 \pi r^2 \). Thus, each cell on a given sphere gets at least one ray. Densities are interpolated bi-linearly.

For each location \((r, \theta, \phi)\), the energy loss is determined by

\[
\frac{dL}{dr} = L(r) - L(r + dr) = \frac{4 - l}{12} L_0 \left( e^{-\tau(r)} - e^{-\tau(r + dr)} \right),
\]

with the central (stellar) luminosity \( L_0 \) and the local optical depth (measured from the UV source)

\[
\tau(r) = \int_0^r n(\text{HI}) C_{\text{abs}} dr,
\]

where \( n(\text{HI}) \) is the atomic hydrogen particle density, and \( C_{\text{abs}} = 1.0 \times 10^{-23} \text{cm}^2 \) is the PAH absorption cross section per H-atom. The factor \( 4 - l / 12 \) accounts for the ray splitting: The base level consists of 12 rays, each of which spawns 4 children at the next refinement level \( l \). The radial step size is \( dr \), thus the volume at each location is known, and \( dL \) can be multiplied by the corresponding volume expression, resulting in the actual UV-energy loss. We integrated over the whole UV-spectrum of the incident radiation field between 912 and 3000 \( \AA \) (see e.g. Li & Draine 2001b, Fig. 1) with the constant absorption cross section \( C_{\text{abs}} \) given above. Furthermore, we assume that all absorbed UV-energy is converted into PAH emission, which we distribute according to the PAH-spectrum by Draine (2003). As shown by Li & Draine (2001b), the spectrum is independent of the radiation field over a large range in intensity. The emitted spectrum, sampled at 30 wavelengths, is convolved with the IRAC response function (Reach et al. 2000) for band 4 at [8.0] micron, which contains the bulk of the PAH emission (Draine 2003). The resulting “gray” emission is integrated along the line of sight (i.e. along a chosen grid axis) following the equation of radiative transfer, including emission and extinction, with an extinction cross section \( C_{\text{ext}} = 1.2 \times 10^{-21} \text{cm}^2 \) per H-atom.

The chosen absorption and extinction cross sections \( C_{\text{abs}}(0.2 \mu m) \) and \( C_{\text{ext}}(8 \mu m) \) are a factor of \( \approx 1.5 \) smaller relative to the values given by Li & Draine (2001b) and Draine (2003). They give values of \( C_{\text{abs}} \approx 1.5 \times 10^{-21} \text{cm}^2 \) and \( C_{\text{ext}} \approx 1.4 \times 10^{-23} \text{cm}^2 \). The slightly smaller cross sections can be accommodated by rescaling the density. Note, however, that in both cases the cross sections for UV and MIR differ by a factor of 100. Thus, material which is optically thick at UV can be optically thin at the re-emitted MIR. In fact, it is to a large extent this difference that leads to the wealth of structure in the observed MIR diffuse emission.
Fig. 3.— Residual image of diffuse emission at [8.0] micron, centered on \((l, b) = (26.9, -0.3)\). Dark absorption regions are predominantly located on the Southern side of the filament.

Fig. 4.— Residual image of diffuse emission at [8.0] micron, centered on \((l, b) = (309.1, -0.4)\). At \((l, b) = (309.00, -0.42)\), there is a “bright-dark” cloud. A “pure” dark cloud can be found at the top of the frame.
4. RESULTS

The irradiation effects will alter the appearance of the cloud, depending on gas density and geometry. The (point) source needs to be subtracted to permit a meaningful analysis of the spatial structure and to facilitate a test of the traditional structure analysis tools, namely power spectra and structure functions. The overall correlation between column density and flux density deteriorates with increasing volume density. Under certain conditions, the flux density maps can even be used to trace the three-dimensional structure of the cloud.

4.1. Morphologies

We begin by discussing the morphology of the irradiated objects depending on the source’s position and the density contrast. The appearance of the irradiated cloud depends strongly on the absolute gas density and on the location of the source.

4.1.1. Irradiated Cloud

Figures 6 – 9 give a first impression of the appearance of an irradiated cloud. The top row of each figure shows the column density along each of the three Cartesian axes. Each column stands for one of the Cartesian coordinate axes along which the model has been projected. The third digit (x, y, z) gives the Cartesian coordinate axis along which the model has been projected. The last digit denotes the logarithm of the density contrast enhancement above the contrast already existing in the simulation, i.e. a value of 2 denotes a density contrast enhancement of $10^2$. Thus, columns are a sequence in position, rows are a sequence in line-of-sight orientation, and each of the four Figures 6 – 9 contains frames of a fixed density contrast. The densities range between $1 \text{ cm}^{-3}$ at the edge of the box (in the “inter-cloud medium”) and $10^2 \text{ cm}^{-3}$ within the cloud for a contrast enhancement of 1, and between 1 and $10^3 \text{ cm}^{-3}$ for a contrast enhancement of 3. Question marks in the model names act as group specifications, e.g. A??0.
refers to all panels in Figure 6, whereas $A?x0$ refers to the panels at varying star position, projected along the $x$-axis (i.e. left column of Figure 6).

For a density contrast of 1 (Fig. 3), the cloud’s column density structure is well traced by the PAH-emission. The object is still optically thin enough for the UV photons to excite its whole volume. Panel A3x0 and the row $A?y0$ show slight self-extinction of the PAH-emission (slightly darkened regions within the cloud). The model sequence $A?y0$ could be compared to Figures 1 and 2.

The extinction structures get more pronounced at the next higher density contrast of 10 or a density range $1 < n($HI$) < 10^3$ cm$^{-3}$ (Fig. 2). Panels $A??1$ tell us more about these regions: The dark structures are a combination of UV-absorption and MIR extinction. Since the star is moving away from the observer from panel A1x1 to panel A3x1, the dark fuzzy region in A3x1 must be located between the star and the observer. If it were solely due to UV-absorption, it should show up as a “bright” (light gray) region in the PAH-emission. The fact that it is dark in the PAH-emission maps thus shows that it is not only a UV-shadowing effect, but that it is also dense enough to extinct the background MIR radiation. A similar effect can be seen in panel A3z1, at the lower left of the cloud. The region is UV-shadowed by the bulk of the cloud, however, in contrast to A3x1, the optical depth in the MIR is smaller, so that while the background MIR is extincted, its brightness is close to the background brightness. As one can see in the corresponding column density map above A3z1, the region is still within the cloud, i.e., there remains gas available for extinction of the MIR. A wisp of denser gas in front of the shadowed region is irradiated by the source, showing up in lighter gray. The effect of the background intensity will be discussed for the model series B.

Increasing the density contrast further to 100, corresponding to a density range of $1 < n($HI$) < 10^4$ cm$^{-3}$, (Fig. 5 panels $A??2$) leads to stronger absorption, and in some cases to complete shadowing. Simultaneously, the diffuse gas – still mostly optically thin for the UV photons – gets brighter. Overall, the maps seem to be more “structured” than their lower density counterparts, which is partly an effect of the combination of emission and extinction, and partly because at higher densities, smaller changes in density are traced out.

That shadowing effects play a large role can be seen in Figures 7 and 8 (models $A??1$ and $A??2$). Moreover, the spatial structure of the cloud continues from the emission regions to the extinction regions (panel A1z2), an effect often seen in the diffuse emission maps (see the examples in 22 and as well as Heitsch et al. 2006). Figure 9 panels $A??3$ stands for the extreme case: It corresponds to a molecular cloud with densities ranging up to $10^5$ cm$^{-3}$. Except for the close vicinity around the star, the object stays dark: all the UV is absorbed directly (see row $A?x,y,z$). In panel A3z3, we actually catch a glimpse of the far side of the cloud: the irradiating source is on the far side of the cloud, and while the cloud is optically thick to the exciting UV, it is still (marginally) optically thin for the PAH-emission. The “dark fuzzy” region discussed in A3x1 is still visible and has acquired a “halo” of excited PAHs.

The irradiation by the central star introduces shell-like patterns in an object that does not have any shell struc-
Fig. 6.— Irradiated cloud (model A770) seen along the three coordinate axes $x, y$ and $z$. The top row gives the column density in cm$^{-2}$. The star is shifted through the volume along the $z$-axis (see text). The flux units are arbitrary. The density contrast is 1. Shown are maps corresponding to the IRAC band 4. Key to the label names: First digit: model series (here: A). Second digit: stellar position in units of $L/4$ along the $x$-axis: A value of 1 stands for the star being located between observer and cloud (bottom left), 2 for at the box center, and 3 for the star behind the cloud, as seen along the $x$-axis. Third digit: coordinate axis parallel to line-of-sight. Fourth digit: Logarithm of density contrast. The actual gas density ranges from 1 to $10^2$ cm$^{-3}$. 
Fig. 7.— Irradiated cloud (model A??1) seen along the three coordinate axes x, y and z. The top row gives the column density in cm$^{-2}$. The star is shifted through the volume along the x-axis (see text). The flux units are arbitrary. The density contrast is 10. Shown are maps corresponding to the IRAC band 4. Key to the label names: First digit: model series (here: A). Second digit: stellar position in units of $L/4$ along the x-axis: A value of 1 stands for the star being located between observer and cloud (bottom left), 2 for at the box center, and 3 for the star behind the cloud, as seen along the x-axis. Third digit: coordinate axis parallel to line-of-sight. Fourth digit: Logarithm of density contrast. The actual gas density ranges from 1 to $10^3$ cm$^{-3}$. 

---

Structure Generation by Irradiation
Fig. 8.— Irradiated cloud (model A?72) seen along the three coordinate axes $x$, $y$, and $z$. The top row gives the column density in cm$^{-2}$. The star is shifted through the volume along the $x$-axis (see text). The flux units are arbitrary. The density contrast is 100. Shown are maps corresponding to the IRAC band 4. Key to the label names: First digit: model series (here: A). Second digit: stellar position in units of $L/4$ along the $x$-axis: A value of 1 stands for the star being located between observer and cloud (bottom left), 2 for at the box center, and 3 for the star sitting behind the cloud, as seen along the $x$-axis. Third digit: coordinate axis parallel to line-of-sight. Fourth digit: Logarithm of density contrast. The actual gas density ranges from 1 to $10^4$ cm$^{-3}$.
Fig. 9.— Irradiated cloud (model A3?3) seen along the three coordinate axes $x$, $y$, and $z$. The top row gives the column density in cm$^{-2}$. The star is shifted through the volume along the $x$-axis (see text). The flux units are arbitrary. The density contrast is 1000. Shown are maps corresponding to the IRAC band 4. Key to the label names: First digit: model series (here: A). Second digit: stellar position in units of $L/4$ along the $x$-axis: A value of 1 stands for the star being located between observer and cloud (bottom left), 2 for at the box center, and 3 for the star behind the cloud, as seen along the $x$-axis. Third digit: coordinate axis parallel to line-of-sight. Fourth digit: Logarithm of density contrast. The actual gas density ranges from 1 to $10^5$ cm$^{-3}$.
4.1.2. Embedded Star

Figure 11 is a variation on the previous theme, namely flux density maps of a self-gravitating turbulent medium, irradiated by a star. As before, a sequence in increasing density contrast is shown. One difference between model A and B is obvious: Model B does not exhibit a well-defined irradiated cloud structure (or at least the rims of that). One could see model B as a “close-up” of model A, taken of a small region around the star inside the cloud of model A. In model B, the UV-radiation is mainly stopped by the numerous filaments arising from shock compressions. In addition to those filamentary structures, the emission has a “fog-like” appearance: in contrast to model A, the density within the cloud is already high enough to absorb sufficient UV to trace even low-density regions, and the scales of the frame are smaller by a factor of nearly 15, so that we are seeing the close environment around the O-star. The small black objects visible at the higher density contrasts are self-gravitating cores that have already collapsed. While it is possible to identify irradiated filaments with structure in the column density map (top), the overall agreement between flux density and column density (even for the lowest contrasts) is rather poor. The densities range between 10 and $10^4 \text{cm}^{-3}$ in the original density distribution (density contrast enhancement of 0, model B??0). An enhancement of 1 then corresponds to a maximum density of $3 \times 10^4 \text{cm}^{-3}$, 2 to $10^5 \text{cm}^{-3}$ and finally 3 to $3 \times 10^5 \text{cm}^{-3}$.

The dark regions in the lower row of Figure 11 are reminiscent of the dark clouds in Figure 5, however, for the wrong reason: the observed dark regions arise from back-illumination by the diffuse 8 micron emission along the whole line of sight, while the dark ray-like regions in model B are a result of the complete UV-absorption of the single source available in the model.

Model sequence B does not seem representative of observed diffuse MIR emission. The column density maps prominently exhibit filamentary structure over the whole domain. These filaments are shock fronts caused by the supersonic turbulence in the box. However, they are not reproduced in the flux density map. Obviously, because of their highly transient nature, the filaments contain only little mass, so that they do not represent a major obstacle to the star’s UV-radiation. Stars form in these models predominantly in the (abundant) intersections of filaments. The high shock compression leads to a close to instantaneous destabilization and fragmentation of these intersections, resulting in the formation of collapsed cores after less than one dynamical time in the simulations (see e.g. Klessen et al. 2000, Heitsch et al. 2001a). In other words, cores form too soon in these simulations for the filaments to gather sufficient mass to be seen in MIR diffuse emission.

4.2. Intensity Distributions

Before we can analyze the intensity distributions (this section) and the spatial structure (§4.3), we need to “remove” the central source, which would otherwise dominate the analysis. To that purpose, we average the intensities azimuthally, centered on the flux density peak, and subtract the resulting profile from the frame. An alternative approach would be to just cut off the peak of the intensity corresponding to the central source. However,
this leaves the imprint of the $R^{-2}$-dilution of the radiation field, which is a direct effect of the central source and would confuse the structure analysis. The subtraction of the $R^{-2}$-profile could be seen as a modified photometry algorithm for point sources irradiating a surrounding, optically thin diffuse medium.

The residual frame (Fig. 12) still shows artifacts due to the central source, but the cloud structure is more pronounced than in the “directly observed” maps. Comparing the residual maps to the column density maps (top row of Fig. 6–9) demonstrates that the irradiation — besides introducing additional structure via absorption (dark regions) — generates more small-scale structure than observable in the column density map. This is
most an optical depth effect in the sense that already small increases in the optical depth (shocks, filaments, smooth gradients in the density) leads to additional absorption which then will be traced out by the re-emitted MIR. This effect gets amplified if the “obstacle” uses up all the remaining UV photons in that ray, i.e. if the optical depth changes from $\tau < 1$ to $\tau \gg 1$ within that structure. The result is a bright region facing the central source, and a dark, shadowed region facing away from the source.

Subtracting the central source in model B (Fig. 13) is not as prone to produce artifacts in the residual flux density maps because the model is pretty much isotropic by construction. In contrast, since the cloud center of model A does not coincide with the UV-source, artifacts are unavoidable and easily recognized as darker circular regions.

4.3. Spatial Structure

In the previous section we saw that a “by eye”-comparison of the column density maps and the flux density maps reveals additional structure in the flux density. The next two sections will discuss under which conditions, and how strongly, the irradiation affects structure measures. We test the reliability of two traditional structure analysis tools, namely power spectra and structure functions. Since the flux density maps at higher densities are dominated by global irradiation effects, power spectra turn out to retrieve structure information less reliably than structure functions. The latter can only be trusted if applied to small enough regions not to be influenced by global irradiation effects.

4.3.1. Power spectra

How reliable is the structure information extracted from diffuse emission? Figure 12 gives an impression for our irradiated cloud (model A). The top panel shows the power spectrum for the original column density map, without any source or irradiation. The three lower panels in turn give the spectra of the irradiated cloud including the source (solid lines on top of panels), and the spectra of the residual flux density, i.e. with the central source subtracted as described in §4.2. Obviously, the maps including the source are completely useless for structure analysis: the source dominates the whole spectrum. The slope ranges around $-0.2$ (not shown in the plot). A completely different picture is revealed when analyzing the residual maps: The resulting slopes approach the values of the column density maps. The slightly flatter slopes indicate that irradiation introduces additional small-scale structure. The artifacts introduced by the subtraction of the central source in model A270 are mirrored in the slight hump of the corresponding spectrum around $\log k \approx 0.9$. Note that the power law exponents refer to power spectra, i.e. a Kolmogorov law would be represented by $-10/3$.

To conclude for model sequence A, the power spectra reproduce the original scale distribution within the errors, which however are substantial, due to the circular averaging.

The situation changes drastically for model series B (Fig. 13 right column), because the high-density cores lead to a strong power increase at small scales (basically, they act as noise) in the column density spectrum, which is why this spectrum is much flatter than expected for a turbulent power spectrum (see also Heitsch et al. 2001a for a discussion of this effect). Note that the column densities in the cores range approximately 2 orders of magnitude above the mean column density (Fig. 11). Since only a tiny fraction of a dense core can emit in the MIR, these objects generally do not show up in the emission maps, and then only in extinction. Again, the central source dominates the “uncleaned” spectrum. Thus, in a sense, the MIR maps of model B are more suitable for
structure analysis than the original column density maps—granted that the major part of the map is unaffected by shadowing or self-extinction.

4.3.2. Structure Functions

Structure functions are a more appropriate tool for analyzing the spatial distribution of an incomplete data set, since masking introduces artificial signals in the power spectra. Only pixels with a measurable signal would contribute to structure functions of observational data. However, due to the irradiation and absorption effects the flux density map generally will not cover the whole cloud, as demonstrated in §4.4.1. Thus, in order to compare the column density and flux density maps, we selected the former for column densities \( N > 10^{22} \) cm\(^{-2}\), which traces out the bulk of the cloud. Applying the resulting mask to the flux density maps and determining the structure functions

\[
SF(l) = \langle |F(x) - F(x + l)|^2 \rangle_x
\]

with lag \( l \) and spatial coordinate \( x \), results in Figure 15.

The four top rows belong to model A1\(??\), with the source being offset to smaller \( x \). The three center rows refer to model A2\(??\), with the source dead-center, and A3\(??\), is represented by the four bottom rows, where the source is offset to larger \( x \), so that A3x? refers to a configuration where the cloud is located between observer and source. Each panel shows the structure function of the original column density at \( N > 10^{22} \) (thin line). The structure function for the corresponding flux density is plotted in thick line style. The numbers \( s \) in each panel refer to the logarithmic slope of the structure function,

\[
\log SF(l) \propto l^s
\]

taken over the first decade in \( l \). Although a column density threshold of \( N > 10^{22} \) leads to most of the high-density gas in one contiguous object, there are a few isolated cloud fragments. Since these cloud fragments are separated from the main body of the cloud, they tend to have the largest lags with respect to the main body, however, it turns out that their column densities are close to the mean column density within the main body, so that the structure functions show a drop at large lags. Since Figure 15 is somewhat messy to interpret, Figure 16 summarizes the degree to which the original column density structure information is retrieved from the flux-density maps.

Just looking at the filled symbols (averages over the three coordinate directions) one might get the impression that larger density contrasts lead to more accurately retrieved slopes. This is somewhat surprising. However, the scatter between the three coordinate directions is substantial and suggests to take a closer look at Figures 6–9 again.

As will be shown in §4.5.5, the lowest density contrast allows a “volume-rendering” of the cloud: the medium is optically thin enough so that the exciting UV can light...
up the whole cloud, nearly acting as a uniform background field. If the source is within the cloud, though, it tends to over-represent the volume directly around it. Thus, the best fit is given by A3y0, where the source is located seemingly at the tip of a filament, farthest away from the bulk of the cloud. The effect of over-emphasizing close-by structures can be well observed even in A3y0: above the source, a filament is traced out which does not show up clearly in the column density map. Comparing this to A3x0 we see that it suffers from “neighborhood-illumination” by the source: internal structure of the cloud thus is just smeared out: the flux-density slope is flatter than the column density slope (Fig. 15). A3x0 fares slightly better, although here the source over-emphasizes the ring-like structure close by, leading to a steeper slope. The center-position maps (A2?0) all suffer from the source being located inside the cloud, while models A1?0, where the source (along the x-axis) is located in the front, again tell a mixed story. For A1x0, the source is located at the upper left end of the cloud, in a fairly diffuse environment and sufficiently far away from the bulk of the cloud in order not to affect the structure function (third cross symbol for log \( \Delta n/\Delta n_0 = 0 \) in Fig. 16). For A1x0 and A1y0, the source is already too embedded.

Moving on to the next density contrast, log \( \Delta n/\Delta n_0 = 1 \), again, A3y1 shows the lowest deviation, however, because of the shadowing effects in the cloud’s left (“Eastern”) part, the deviation is larger than for A3y0. That A3x1 provides better fits than A2x1 and A1x1 is understandable again because of shadowing, although it is not directly clear why the match should be better than that for A3x0. Checking the corresponding panels A3x0 and A3x1 in Figure 15 gives the answer: on the small scales, the structure functions agree, however, on large scales they differ. The better matches for A1z1 and A2z1 (compared to A3z1) might be a consequence of the shadowed regions, which still show substructure: this substructure would enter the structure function on the small scales and provide the same information as structure in emission. Thus – granted that we chose a small enough field for analysis – to some extent structure in absorption and emission can be used simultaneously for analysis.

At density contrasts log \( \Delta n/\Delta n_0 = 2 \) and 3, matching between the overall shapes of structure functions for column and flux density deteriorates on the large scales (Fig. 15), as one would expect by looking at Figures 8 and 9. However, there is still enough signal from irradiating small density variations for the structure functions to match on the small scales. Again, given that we take a small enough region, the structure function can be reproduced.

Another limitation on the size of the region is given by the available dynamic range in the observed flux density maps. In the diffuse emission, it often turns out that the dynamic range is spanning 1, at most 2, decades, which...
limits the spatial scales available for analysis.

To summarize, structure functions seem to be a much more viable tool to investigate localized diffuse emission than power spectra. Despite the fact that the irradiation sometimes modifies the underlying density information beyond the point of recognizability, the resulting structure functions still retrieve the salient scale information – given that the field investigated is small enough. Because of the global irradiation effects, there is only little hope to retrieve the large-scale information accurately. The most promising way would be to identify small, “uncontaminated” regions and reconstruct the structure information from those.

The deviations (Fig. 16) are within the errors on the mean of the structure function (see the analysis of power spectra). Again, these stem from the circular averaging. The large deviations in fact point to a major problem when applying two-point correlators to data exhibiting anisotropic structures. For example, filaments will lead to different structure information along and perpendicular to their long axis, in turn leading to a mixing of the spectral information when averaging the directions. Since the observed structure in the interstellar medium seems to be anisotropic to a large extent, the application of unmodified two-point correlators might raise questions. We will discuss this problem and possible remedies in a future paper.

### 4.4. Correlation Measures

How reliably are structures in column density reproduced in the flux density maps? The correlation coefficient

$$\langle C(N, F) \rangle = \frac{\sum (N_{ij} - \langle N \rangle) (F_{ij} - \langle F \rangle)}{\sqrt{\sum (N_{ij} - \langle N \rangle)^2} \sqrt{\sum (F_{ij} - \langle F \rangle)^2}}$$

(5)

serves as a first crude estimator for the similarity of column density maps $N_{ij}$ and flux density maps $F_{ij}$. The means over the map are denoted by $\langle N \rangle$ and $\langle F \rangle$ respectively. For all density contrasts larger than 1, $N$ and $F$ are basically uncorrelated (Fig. 17).

The correlation coefficient provides an overall estimate for how “similar” the maps are. Unfortunately, equation (5) is only of limited use for a point-to-point similarity measure. Although one could plot a map of the summands, the normalization is unclear. One possible similarity measure is given by

$$C(N, F) = \frac{N - \langle N \rangle F - \langle F \rangle}{\langle N \rangle \langle F \rangle},$$

(6)

At locations where both maps show either strong or weak signals, $C > 0$, while positions with anti-correlated signals will exhibit $C < 0$.

Figure 18 shows $C(N, F)$ for model A. It can be directly compared to Figures 6–8 and 12. For the lower density contrasts, the column density map correlates well with the emission (light gray to white shades), while for higher density contrasts, the absorption regions lead to a strong anti-correlation. The overall positive correlation deteriorates for larger density contrasts.

#### 4.5. PAH-Emission as Edge Sensor

If the UV from the central source excites PAH-emission in the rims of the surrounding molecular cloud, the emitted flux density could be used as an edge sensor or gradient indicator. To test this, for each position in the simulation domain and the column density map we calculate the 3D radial density gradients

$$\partial_R \rho(R_{i,j,k}, \theta_{i,j,k}, \phi_{i,j,k}) \equiv \left(\frac{\hat{\rho} - \rho}{\Delta R}\right)_{i,j,k},$$

(7)

and the two-dimensional column density gradients respectively

$$\partial_r N(r_{i,j}, \phi_{i,j}) \equiv \left(\frac{\hat{N} - N}{\Delta r}\right)_{i,j}.$$

(8)

The hatted quantities are bi-linear interpolations of the (column) density at the positions

$$\hat{\rho} \equiv \rho(X_i + \Delta R \sin \theta \cos \phi, Y_i + \Delta R \sin \theta \sin \phi, Z_i + \Delta R \cos \theta),$$

$$\hat{N} \equiv N(x_i + \Delta r \cos \phi, y_i + \Delta r \sin \phi),$$

(9)

(10)
with $R \equiv \sqrt{x^2 + y^2 + z^2}$ and $r \equiv \sqrt{x^2 + y^2}$. The radial increments $\Delta R$ and $\Delta r$ measure one grid cell, and $\theta$ as well as $\phi$ in equations (9) and (10) refer to the coordinates $(i, j, k)$, $(i, j)$ respectively. The gradients are computed with respect to the central source ($R = 0$ and $r = 0$ at position of source) and selected for positive values (Figs 14, 20). Positive gradients $\partial_R \rho > 0$ indicate locations of enhanced UV-absorption and thus enhanced PAH-emission, while $\partial_i \rho$ would denote the same if the physical cloud structure were truly 2D. We compute $\partial_R \rho$ and $\partial_i \rho$ for each cell in the simulation domain and column density map respectively, i.e. a slight subtlety enters regarding the 3D-case: We still need to project the gradients on a plane. In order to keep the 3D-information at least partially, we color-coded the distance along the line of sight, where blue colors denote short distances (towards the observer) and red colors denote long distances (at the far end of the volume). The intensity gives the strength of the gradient. The distance information is weighted with the gradient strength, i.e. two gradients of same strength located at one quarter and at three quarters of the box length will show up in purple.

At first sight, the correspondence between gradient maps and flux density is at most poor. A close look however reveals some interesting details. We focus on Figure 15 (models A2?1 and A2?2) first. The top row shows the original column density, followed by the 2D gradient $\partial_i \rho$ and the projected 3D gradient $\partial_R \rho$. The two bottom rows give the flux density maps for models A2?1 and A2?2, i.e. for increasing density contrast. The color scale is a measure of the location of the gradient, with blue closest to the observer, and red at the far end of the box. Clearly, the gradients making up the map come from all possible locations along the line of sight. Taking A2?1, the L-shaped structure visible in extinction in the flux-density maps is traced out by a hazy bluish gradient-indicator: The corresponding density jump is close to the observer, which makes sense, since dense material between the source and the observer leads to the extinction. Further right of the L-shape, the gradient map of A2?2 shows a red (albeit dark) region: weak gradients at the far side of the source. Correspondingly, we see a bright irradiated region in the flux density map of A2?1: the (far away) structures are irradiated by the central source. This is not seen anymore in A2?2: the density has increased and leads to extinction of the far-away emission. Similarly, the dark region to the lower left of the center in A2?1 corresponds to gradients close to the observer. In this case however, there is no clear blue signal in the 3D gradient map, which indicates that the dark region is caused by a combination of UV-shadowing and MIR extinction of diffuse background. Moving northwards of that direction, the source of emission is receding from the observer: again, this information is lost at higher density contrast (A2?2), and thus the cloud structure is only incompletely “sampled”. Interestingly, for A2?2, the situation is nearly converse: the dark gradient-regions link up with strong emission signals (to upper left of the center), while the extincted regions to the South are farther away from the observer. Thus, those dark regions might again be caused by a combination of missing irradiation and extinction of diffuse background. The “handle” to the right is located at the far side of the central source.

Compared with this richness of structure, the 2D gradients come as sort of a big disappointment: They resemble the cloud structure only in the widest sense. Beginning with A2?1 again, the L-shape is recovered, but this is already all we can see. For A2?2, the “handle” to the right of the central source is showing up slightly in $\partial_i \rho$. However, moving to the larger density contrast (A2?2), the situation changes slightly: The flux density maps look more “rim”-like, more easily identified with the 2D gradient map. Carrying this idea to the extreme, Figure 20 shows the gradient maps and flux densities for A1?3 (as Fig. 19 shows, model A2?3 would be not exactly informative in this context). The 3D gradients now are hardly reproduced (with the noticeable exception of the Southern absorption rim in A1x3). The 2D gradients however tend to trace now the absorption rims (see e.g. A1y3 and A1z3). Thus, for lower density contrasts, or a more diffuse environment, the emission structures are intrinsically 3D, while for higher density regions, they tend to get more and more 2D (although 3D effects are still not to be neglected).
by Foster & Goodman (2006). Since they were interested for the NIR, based on the observations of “cloudshine” medium. Padoan et al. (2006) supported this possibility resolution study of the column density structure of the medium. Our models, and how this affects the structure analysis, reliable flux density maps reproduce column density in MIR extinction. In the following, we will summarize how which then is integrated along the line-of-sight, including PAHs absorb the UV and re-emit the energy in the MIR, inside a molecular cloud, both irradiated by an O5 star. "molecular" cloud, and the other imitating a region deep model sets, one corresponding to a (more or less) isolated underlying (column) density information. We used two maps of diffuse emission in the MIR to reproduce the interpretation. We quantified the reliability of flux-density GLIMPSE, we identified possible limitations of this in- terpretation – given that the field investigated is small enough not structure functions still retrieve the salient scale informa- tion beyond the point of recognizability, the resulting structure functions seem to be a more viable tool to in- vestigate localized diffuse emission. Despite the fact that the irradiation may modify the underlying density in the appearance of the diffuse emission, they used an isotropic radiation field mimicking a UV background, in contrast to our models that employ a point source for irradiating the surrounding medium. For higher-density environments such as molecular cloud in the vicinity of strong UV sources, interpreting MIR emission as column density requires some caution: The transition from $\tau < 1$ to $\tau > 1$ can lead to strong signals in the MIR flux density, but not necessarily paired with a corresponding signal in the column density: The maps bear no resemblance to the column density (Figs. 9 and 11). In the extreme case, PAH-emission is only excited at the rims of clouds (e.g. Churchwell et al. 2006), causing the impression of a highly filigree structure in the gas: irradiation introduces more small-scale structure than observable in the under- lying column density maps. As soon as shadowing is obvious, the structure seen in emission will generally not represent column density. Some of the observed shell-like structures could be just irradiation effects, and by themselves indicate that shadowing (or “rimming”) has set in (Figs. 6, 7 and 10). Since our models do not in- clude PAH destruction around the star, we expect them to exhibit fewer shell-like structures than observed. PAH cavities would lead to “shells” even if the cavities were not associated with e.g. wind-blown bubbles. 5.2. Structural Properties Power spectra are only partially useful for an analysis of diffuse emission structure. Their well-known main drawback is that they tend to confuse the information about extent of a region and the separation of regions. Furthermore, masking is always an issue in power spectra, since it tends to introduce a signal by itself. Power spectra containing the central source are completely dominated by that (Fig. 14 left column), while spectra of residual maps are slightly flatter than the underlying column density distribution. This could be a projection effect and/or the result of additional small-scale structure traced out by irradiation. The spectral slope is pretty much insensitive to the density contrast within the error bars, which are significant. For collapsed regions (Fig. 14 right column), the column density spectrum flattens considerably because of the strong point source contribution. Compared to that, the flux density spectra steepen because the point sources are not fully irradiated and thus do not show up (except in extinction). Structure functions seem to be a more viable tool to inves- tigate localized diffuse emission. Despite the fact that the irradiation may modify the underlying density information beyond the point of recognizability, the resulting structure functions still retrieve the salient scale information – given that the field investigated is small enough not to be contaminated by global irradiation effects. There is little hope to retrieve the large-scale information accurately by applying a global structure measure such as power spectra. Structure in extinction can be used as a continuation of structure seen in emission, although this raises the issue of an appropriate choice of background for the extincted region (Figs. 9 and 10). The deviations (Fig. 10) are within the errors on the mean of the struc- ture function. Since the overall structure in the ISM tends to be anisotropic, applying two-point correlators seems at least

![Gradient maps (see text) for model A, source at position 1 (A1??).](image-url)
questionable. Averaging in k or l space leads to substantial errors on the mean, which themselves indicate that the underlying structure is anisotropic to a large extent.

The application of these results to actual observational data (GLIMPSE) and the discussion of anisotropy we defer to a future paper.

5.3. Flux density as gradient indicator

Since the conversion of UV to MIR will occur predominantly at regions of large positive radial density gradients (as long as there are photons left), the flux density maps might offer the opportunity to gather information about the (3D) density structure of the cloud. To test this, we compared the radial volume and column density gradients to the flux density maps. For lower density contrasts, the flux density maps tend to trace out the 3D structure of the cloud, and in fact they can be used as 3D gradient indicators. For higher density contrasts, they revert to an indicator of the column density gradients: the structures seemingly become two-dimensional. Thus, more diffuse regions are intrinsically “more 3D”, while higher-density environments tend to be 2D.

5.4. Limitations

Beside the irradiation effects discussed here, there are other limitations to an interpretation of flux density maps as column density.

(1) If the volume density is low enough that the exciting UV can irradiate the whole cloud, one might question how long the line-of-sight actually is, and whether angular effects leading to scale-mixing in a structure analysis would play a role.

(2) On the other hand, the volume density might be large so that the irradiating UV will be absorbed more or less directly “at the rim” (if such a thing exists) of the cloud. Then, depending on the geometry of observer, irradiated medium and irradiation source, the observer might see predominantly 1D structures or 2D structures, implying projection effects in the spectral information.

5.5. Conclusions

We thank E. Bergin for a critical reading of the manuscript. Computations were performed at the NCSA (AST040026) (FH) and on the SGI-Altix at the USM, built and maintained by M. Wetzstein and R. Gabler. Support for this work was provided by the University of Michigan (FH), NASA’s Astrophysics Theory Program (NNG05GH35G) (BW), the Spitzer Space Telescope Legacy Science Program through contracts 1224988 (BW) and 1224653 (EC, BB, MM) and NASA’s Spitzer Space Telescope Fellowship Program (RI).

REFERENCES

Benjamin, R. A., et al. 2003, PASP, 115, 953
Bethell, T., Zweibel, E. G., Heitsch, F., & Mathis, J. S. 2004, ApJ, 610, 801
Churchwell, E., et al. 2004, ApJS, 154, 322
Churchwell et al. 2006, ApJ, submitted
Draine, B. T. 2003, ARA&A, 41, 241
Foster, J. B., & Goodman, A. A. 2006, ApJ, 636, L105
Görski, K. M., Hivon, E., Banday, A. J., Wandelt, B. D., Hansen, F. K., Reinecke, M., Bartelmann, M. 2005, ApJ, 622, 759
Heitsch, F., Mac Low, M.-M., & Klessen, R. S. 2001, ApJ, 547, 280
Heitsch, F., Zweibel, E. G., Mac Low, M.-M., Li, P., & Norman, M. L. 2001, ApJ, 561, 800
Heitsch, F., Slyz, A. D., Devriendt, J. E. G., Burkert, A. 2006, submitted
Heitsch, F., Slyz, A. D., Indebetouw, R., Meade, M. R., Babler, B. L., Churchwell, E. 2006, in preparation
Kim, S.-H., Martin, P. G., & Hendry, P. D. 1994, ApJ, 422, 164
Klessen, R. S., Heitsch, F., & Mac Low, M.-M. 2000, ApJ, 535, 887
Léger, A., d’Hendecourt, L., Défoue’, D. 1989, à, 216, 148
Li, A., & Draine, B. T. 2001, ApJ, 550, L213
Li, A., & Draine, B. T. 2001, ApJ, 554, 778
M. 2006, ApJ, submitted
Peeters, E., van Diewenhoven, B., van Kerckhovens, A., Hony, S., Tielens, A. G. G. M., Allamandola, L. J., Hudgins, D. M., & Bauschlicher, C. W. 2003, Astrophysics of Dust, 41
Reach et al. 2006, The IRAC Handbook, [http://ssc.spitzer.caltech.edu/IRAC/dh/]
Schnee, S., Bethell, T., & Goodman, A. 2006, ApJ, 640, L47
Slyz, A. D., Devriendt, J. E. G., Bryan, G., & Silk, J. 2005, MNRRAS, 356, 737
Slyz, A. D., Devriendt, J. E. G., Bryan, G., Heitsch, F., & Silk, J. 2005, MNRRAS, submitted
Stetson, P. B. 1987, PASP, 99, 191
Whitney, B. A. et al. 2004, ApJS, 154, 315