ULTRAVIOLET ESCAPE FRACTIONS FROM GIANT MOLECULAR CLOUDS DURING EARLY CLUSTER FORMATION

COREY HOWARD\textsuperscript{1}, RALPH PUDRITZ\textsuperscript{1,2,3,4}, AND RALF KLESEN\textsuperscript{2,5}

\textsuperscript{1} Department of Physics and Astronomy, McMaster University, 1280 Main St. W, Hamilton, ON L8S 4M1, Canada
\textsuperscript{2} Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische Astrophysik Albert-Ueberle-Str. 2, D-69120 Heidelberg, Germany

Received 2016 September 29; revised 2016 November 4; accepted 2016 November 13; published 2016 December 29

ABSTRACT

The UV photon escape fraction from molecular clouds is a key parameter for understanding the ionization of the interstellar medium and extragalactic processes such as cosmic reionization. We present the ionizing photon flux and the corresponding photon escape fraction ($f_{\text{esc}}$) arising as a consequence of star cluster formation in a turbulent, $10^6 \, M_\odot$ giant molecular cloud, simulated using the code FLASH. We make use of sink particles to represent young, star-forming clusters coupled with a radiative transfer scheme to calculate the emergent UV flux. We find that the ionizing photon flux across the cloud boundary is highly variable in time and space due to the turbulent nature of the intervening gas. The escaping photon fraction remains at $\sim 5\%$ for the first 2.5 Myr, followed by two pronounced peaks at 3.25 and 3.8 Myr with a maximum $f_{\text{esc}}$ of 30% and 37%, respectively. These peaks are due to the formation of large H II regions that expand into regions of lower density, some of which reaching the cloud surface. However, these phases are short-lived, and $f_{\text{esc}}$ drops sharply as the H II regions are quenched by the central cluster passing through high-density material due to the turbulent nature of the cloud. We find an average $f_{\text{esc}}$ of 15% with factor of two variations over 1 Myr timescales. Our results suggest that assuming a single value for $f_{\text{esc}}$ from a molecular cloud is in general a poor approximation, and that the dynamical evolution of the system leads to large temporal variation.

Key words: galaxies: star clusters: general – H II regions – ISM: clouds – methods: numerical – radiative transfer – turbulence

1. INTRODUCTION

The escape of UV photons from massive stars in young star clusters within molecular clouds drives many critical processes in the interstellar medium (ISM) and intergalactic medium (IGM). The radiation released by stars contributes to the interstellar radiation field (ISRF), which has the highest energy densities at optical and UV wavelengths (Draine 2011), the strength of which was first estimated by Habing (1968) to be $\sim 4 \times 10^{-14}$ erg cm$^{-3}$ for 12.4 eV photons. Later authors have further characterized the strength of the UV portion of the ISRF by including wavelength dependence (Draine 1978; Mathis et al. 1983).

The ISRF, as well as its interactions with gas and dust, is responsible for determining the chemical, thermal, and ionization state of the ISM via photoionization, photodissociation, photoelectric heating, and absorption and re-emission by dust grains (Draine 2011). Since most UV photons are generated by massive stars in the range 10–100 $M_\odot$, they contribute significantly to the strength of the ISRF and significantly alter the state of the ISM in their vicinity, even when considering their short lifetimes.

It has also become clear in recent years that UV ionizing photons from galaxies hosting active galactic nuclei (AGNs) are not sufficient to completely reionize the IGM by $z = 6$ (Fan et al. 2006; Robertson et al. 2013). Instead, fainter dwarf galaxies, with masses as low as $\sim 10^8 M_\odot$, are needed to provide the remaining UV photons via their stellar content (Wise et al. 2014; Xu et al. 2015). These low-mass galaxies may contribute up to $\sim 40\%$ of the total ionizing photons required for reionization (Wise et al. 2014).

In order to contribute to reionization, ionizing photons produced in these galaxies must escape into the IGM (Robertson et al. 2010). The exact fraction of photons, $f_{\text{esc}}$, that escape their host galaxies, however, is a debated topic. For bright, high-redshift galaxies, measured via the Lyman continuum, $f_{\text{esc}} \sim 7\%$ (Siana et al. 2015), but this number can be as high as $\sim 30\%$ for fainter Ly$\alpha$-emitting galaxies (Nestor et al. 2013). Estimates of $f_{\text{esc}}$ from the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) based on H II region mapping suggest global escape fractions of 4% and 11%, respectively (Pellegrini et al. 2012).

Simulations that attempt to quantify $f_{\text{esc}}$ for both high- and low-mass galaxies have been performed, but these results often vary by orders of magnitude. For example, Paardekooper et al. (2011) found $f_{\text{esc}} < 1\%$ for high-redshift dwarf galaxies, while later numerical works have found $f_{\text{esc}} > 10\%$ (Razoumov & Sommer-Larsen 2010; Ferrara & Loeb 2013; Paardekooper et al. 2015). Moreover, $f_{\text{esc}}$ can vary by orders of magnitude over the lifetime of the galaxy (Paardekooper et al. 2011).

As illustrated by the numerical simulations in Paardekooper et al. (2011), the distribution of dense gas in star-forming regions is one of the main constraints on $f_{\text{esc}}$ from a galaxy. This suggests that detailed modeling of $f_{\text{esc}}$ from dense regions within galaxies is required to fully understand the trends observed in more global simulations. Giant molecular clouds (GMCs) are the densest regions of the galactic ISM, and they are the sites where all known star formation takes place. Studying the escape of UV photons from GMCs is therefore also important for a better understanding of cosmological reionization.
The GMC environment is complex, consisting of filaments produced by supersonic turbulence out of which stars and clusters ultimately form (Bertoldi & McKee 1992; Lada & Lada 2003; Mac Low & Klessen 2004; McKee & Ostriker 2007; André et al. 2014; p. 27, Klessen & Glover 2016). Stars that form in this environment can then alter their surroundings via the emission of radiation, producing H II regions. The complexity of this problem necessitates the use of numerical simulations. While simulations of GMCs that include star formation and radiative transfer have been completed (Dale et al. 2005; Krumholz et al. 2010; Murray et al. 2010; Peters et al. 2010a; Bate 2012; Klassen et al. 2012b; Walch et al. 2013), these studies do not examine the fraction of photons that escape the cloud.

In this paper, we address the critical question of UV escape fractions from turbulent molecular clouds by computing \( f_{\text{esc}} \) from \( 10^6 M_\odot \) GMCs. We employ our suite of simulations that simulated star cluster formation and radiative feedback within young, \( 10^6 M_\odot \) GMCs that have varying initial virial parameters (Howard et al. 2016). We model the evolution of star clusters, defined here as less than 5 Myr, since the effects of supernovae are not included. We found that, despite producing large H II regions, the inclusion of radiative feedback only suppressed the formation of clusters by a few percent. In comparison, varying the initial virial parameter from 0.5 to 5 (i.e., bound to unbound) reduced the efficiency of cluster formation by \( \sim 34\% \). The high final star formation efficiencies, which range from 18% to 34%, suggest that radiative feedback alone is not responsible for limiting star formation but that initially unbound clouds better reproduce locally observed GMCs.

Given that we have computed the structure and dynamics of cluster-forming clouds undergoing radiative feedback, we can now address the question of what fraction of the UV photons produced by the massive stars in clusters escapes the molecular cloud.

We present maps of the ionizing photon flux escaping the cloud to demonstrate its highly nonuniform nature in space. We also present \( f_{\text{esc}} \) (used hereafter to represent the escape fraction from a GMC) during the first 4 Myr of the GMC’s evolution, which is shown to be highly variable in time and peaks at \( \sim 35\% \) with a long-term average value of \( \sim 15\% \). The variable nature of \( f_{\text{esc}} \) is attributed to H II regions that dramatically vary in both shape and size due to the dynamical nature of the gas and embedded clusters.

2. METHOD

Below, we provide a brief description of our numerical methods and subgrid model for star cluster formation.

We have simulated a \( 10^6 M_\odot \) GMC using the adaptive mesh refinement (AMR) code FLASH (Fryxell et al. 2000), which includes self-gravity, radiative transfer, star cluster formation, and cooling processes (see Howard et al. 2016 for more detail). This cloud mass was chosen in particular because high-mass GMCs contain most of the molecular mass in the Milky Way and are host to the most massive stellar clusters (Mac Low & Klessen 2004; McKee & Ostriker 2007; Klessen & Glover 2016).

The cloud is initially overlaid with a turbulent velocity field that is composed of a mixture of solenoidal and compressive turbulence with a Burgers spectrum (as in Girichidis et al. 2011). We selected a configuration with an initial virial parameter of 3, corresponding to an initial Mach number of 73. We chose this simulation in particular out of the suite presented in Howard et al. (2016) because we found that initially unbound clouds best reproduce the properties of massive GMCs in the Milky Way. The radius of the cloud is 33.8 pc. The initial average density of the GMC is \( n = 100 \text{ cm}^{-3} \), with a density profile that is uniform in the inner half of the cloud and decreases as \( r^{-3/2} \) in the outer half.

The package PARAMESH is used for the adaptive mesh portion of FLASH (Fryxell et al. 2000). The grid is refined at locations with sharp density or temperature contrasts to improve the resolution near filaments and H II regions. The minimum cell size in our simulation is 0.13 pc.

To model gas cooling, we employ the method from Banerjee et al. (2006), which treats cooling via molecular line emission, gas–dust interactions, \( \text{H}_2 \) dissociation, and radiative diffusion in the optically thick limit. The cooling rates from Neufeld et al. (1995) are used to treat molecular line emission, while the treatment in Goldsmith (2001) cools the gas via gas–dust transfer.

Radiative transfer is treated via a hybrid-characteristics ray tracer developed by Rijkhorst et al. (2006) and adapted for astrophysical use by Peters et al. (2010a). This scheme treats both ionizing and nonionizing radiation and makes use of the DORIC package (Mellema & Lundqvist 2002) to solve the ionization equations. While the DORIC package is capable of treating a large number of species, we consider hydrogen to be the only gas component for simplicity. The flux of ionizing photons, \( F_\text{s} \), from an individual source is given by

\[
F_\text{s} = \frac{S_\text{s}}{4\pi r^2} e^{-\tau},
\]

where \( S_\text{s} \) is the cluster’s ionizing photon rate in \( \text{s}^{-1} \), \( r \) is the distance between the source and cell of interest, and \( \tau \) is the intervening optical depth. The opacity to nonionizing radiation is represented by the Planck mean opacities from Pollack et al. (1994), which are used because the ray tracer has no frequency dependence. We adopt a single UV opacity in neutral gas of \( \kappa = 775 \text{ cm}^2 \text{s}^{-1} \) from Li & Draine (2001). This opacity is scaled by the neutral fraction of the gas, so completely ionized regions have an opacity of zero.

We make use of sink particles (Federrath et al. 2010) to model star cluster formation with a custom subgrid model to represent star formation within the clusters (Howard et al. 2014). We adopt a threshold density for formation of \( 10^4 \text{ cm}^{-3} \), which is based on observations of star-forming clumps (Lada & Lada 2003). Our subgrid model within cluster sink particles (henceforth referred to as clusters) divides the cluster mass into two types: stars, and the remaining gas mass (denoted as the reservoir). We convert the reservoir to stars by randomly distributing the mass into main-sequence stars via a Chabrier (2005) initial mass function (IMF) with an efficiency of 20% per free-fall time, where the free-fall time is taken to be 0.36 Myr. The IMF is sampled every 1/10 of a free-fall time to allow cluster properties to evolve smoothly over time. Newly accreted gas is added to the reservoir (i.e., gas that is available for star formation during the next IMF sampling step). The masses of all stars formed in the cluster are recorded, and analytical fits provided by Tout et al. (1996) are used to determine each star’s total and ionizing luminosity. The cluster’s luminosity is then the sum of its consituents, which is then used by the ray tracer.
In order to reduce the computational time, we apply a mass threshold of $1000 \, M_\odot$ in stars (which typically have $\sim$1 O star), below which clusters do not radiate. Clusters below the threshold continue to accrete gas and form new stars, but they are not included in the radiative transfer calculation.

3. RESULTS

To study the spatial distribution of the escaping UV flux from the cloud, we produce maps of the ionizing flux across a spherical surface, which are presented in Figure 1. The radius of this sphere corresponds to the initial cloud radius of 33.8 pc, and all clusters are contained within the surface. The maps were made using a Hammer projection, which was chosen because it is an equal-area projection. We also include the locations of the 10 most luminous clusters (accounting for 93% of the final ionizing luminosity), projected to the closest location on the sphere, in white circles. Note that the clusters are not actually located on this spherical surface, but are contained within its volume.

The first panel, plotted at 1.5 Myr, shows the ionizing flux shortly after the first clusters begin to radiate. A large fraction of the surface is not receiving any ionizing photons, shown by the white patches. This is because at this time, the clusters have only recently formed (meaning that their total ionizing luminosity is low compared to their final values).

In the same panel, the regions that are receiving ionizing photons are concentrated in the upper right quadrant. Note that the most luminous clusters appear in a grouping toward the right side as well, suggesting that these clusters are responsible for much of the emission observed outside the cloud. There is also some flux associated with the cluster in the bottom left quadrant of this panel.

Figure 1. Maps of the ionizing photon flux across a spherical surface of radius 33.8 pc (corresponding to the initial GMC radius) shown at six different times. White circles represent the closest location of the 10 most luminous clusters to the sphere. More luminous clusters are shown by larger circles. The maps were produced using a Hammer projection, which is an equal-area projection.
At 2.5 Myr, we see that the entire surface is now being traversed by UV photons from the clusters. The flux of photons, however, is not spatially uniform. Since the flux on the sphere’s surface depends on the intervening column density, the presence of dense clumps and filaments manifests itself as regions with lower flux. We note that the simulation has virialized ($\alpha = 1$) at 2.5 Myr, so any further turbulence is driven by gravitational collapse of the gas (see Howard et al. (2016) for details and Klessen & Hennebelle (2010) for a more general discussion of accretion-driven turbulence).

As the total ionizing luminosity increases and the total mass in gas decreases, the presence of these dark filaments becomes less pronounced. At 3.18 Myr, only the left side of Figure 1 shows regions with low flux. The grouping of clusters on the right of this figure is likely responsible for the higher flux in that region. From 3.75 Myr onward, the flux is more spatially uniform due to increased cluster luminosities and lower total gas mass.

The above visualizations show that the ionizing flux can vary significantly over both space and time within a GMC. Its time evolution is shown in the top left panel of Figure 2. Note that we only include the clusters that are above the mass threshold discussed in Section 2, since clusters below this threshold are not included in the radiative transfer calculations.

The total escape fraction remains low at approximately 3% between 1.5 and 2.5 Myr. After 2.5 Myr, $f_{\text{esc}}$ rises to a peak of 30% at 3.25 Myr, followed by a sudden drop. The escape fraction begins to rise again, reaching a peak of 37% at 3.8 Myr. The average $f_{\text{esc}}$ from the first rise at 2.5 Myr to the end of the simulation, shown by the horizontal line, is 15%.

The rising $f_{\text{esc}}$ and subsequent rapid drops are not due to changes in the ionizing photon output from the clusters, which is shown in the top right panel of Figure 2. These clusters are accreting new gas vigorously from their surroundings and building new, massive stars as time progresses. The increase in the ionizing photon output is steady and shows no distinct features that correspond to the features seen in $f_{\text{esc}}$.

Rather, the ionization structure of the gas is responsible for the variable $f_{\text{esc}}$. In the bottom left panel of Figure 2, we plot the fraction of gas mass that has an ionization fraction of greater than 95%. This figure clearly mirrors the features seen in $f_{\text{esc}}$, with an increasing $f_{\text{esc}}$ corresponding to an increase in the mass fraction of ionized gas. Recall that UV opacity in ionized regions is significantly lower than in neutral regions.

Figure 2. Top left: total UV escape fraction across the spherical surface presented in Figure 1. The vertical lines, shown in all panels, correspond to the times shown in Figure 1 (1.50, 2.51, 3.18, 3.31, 3.75, and 4.10 Myr). The horizontal line shows the average $f_{\text{esc}}$ from 2.5 to 4.2 Myr. The escape fraction is defined here as the total number of photons crossing the surface divided by the total number of photons being produced by the clusters. Note that we only include clusters above the mass threshold described in Section 2, since clusters below this threshold are not included in the radiative transfer calculations. Top right: total ionizing photon rate produced by clusters above the mass threshold for radiation. Bottom left: fraction of gas, by mass, that has an ionization fraction of greater than 95%. Bottom right: mass evolution of the four most massive clusters, shown for reference. Discrete jumps in mass are due to cluster-merging events. The complete mass evolution tracks can be found in Howard et al. (2016).
While the change in the ionized mass fraction is low, peaking at $\sim 3\%$, the HII regions can spatially occupy a significant fraction of the simulation volume, typically filling large voids that are interspersed between dense filaments. Since clusters are the source of radiation and therefore tend to exist in HII regions, photons can travel large distances due to the reduced opacity, resulting in higher photon fluxes near the boundary of the simulation volume.

However, the size and shape of HII regions are not constant. Both observations (De Pree et al. 2014, 2015) and simulations (Peters et al. 2010a, 2010b; Galván-Madrid et al. 2011; Klassen et al. 2012a) show that the size of an HII region can fluctuate on short timescales, a phenomenon described as “flickering.” The dynamic and anisotropic nature of the gas, in combination with dynamic clusters, can result in HII regions becoming shielded to radiation due to changes in density between the source and the ionized regions. The formerly irradiated gas then recombines, causing the HII to flicker.

A visual demonstration of this flickering is displayed in Figure 3, which shows three-dimensional (3D) images of density (in green) and HII regions (in red). The green density contours show gas at $\sim 100 \text{ cm}^{-3}$, which is the typical density of the filaments out of which the clusters form. The entire simulation volume is shown, and the box side length is 83 pc.

The left panel of Figure 3 shows the state of the simulation at 3.18 Myr, corresponding to the first pronounced peak in $f_{\text{esc}}$. A large HII region has developed on one side of the cloud that extends away from the dense, central gas to the boundary of the simulation volume. The middle panel, shown at 3.31 Myr, shows the decrease in the size of the HII region that is responsible for the deep trough in $f_{\text{esc}}$ at 3.25 Myr. The right panel of Figure 3, plotted at the second peak of $f_{\text{esc}}$ at 3.75 Myr, shows that the HII region has expanded again to a similar size to that seen in the first panel.

To investigate the cause of the variable HII region size, we focus our analysis on one luminous cluster that is associated with the HII region. This cluster is the second most luminous in the simulation with a final ionizing luminosity of $1.40 \times 10^{51} \text{ s}^{-1}$. The most luminous cluster was not chosen because it is deeply embedded in the dense, central gas and therefore its associated HII region is small in comparison to the one that extends to the boundary of the simulation volume, as seen in Figure 3.

We drew lines of sight that originate at the cluster’s position and extend a distance of 20 pc through the large HII region. This was done at two times, one just before the HII region collapses for the first time (at 3.25 Myr) and one immediately after the collapse ($\sim 35,000$ yr after the first image). We can then examine how the density and the recombination rate differ before and after the HII region collapses along these lines of sight.

We find that the radiative recombination rate along the lines of sight increases significantly immediately after the HII region collapses, increasing from $\sim 5 \times 10^{-8}$ to $1 \times 10^{-6} \text{ cm}^{-3} \text{s}^{-1}$. The radiative recombination rate is given by $\alpha n^2$, assuming an ionization degree of 100%, where $\alpha$ is the radiative recombination coefficient and $n^2$ is the square of the number density. The recombination coefficient varies with temperature as

$$\alpha = 2.59 \times 10^{-13} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.7}$$

where $T$ is the gas temperature in Kelvin.

The radiative recombination rate increases after the collapse for two reasons. First, the density immediately surrounding the cluster increases, likely due to the turbulent nature of the surrounding gas. Second, as the region cools, the recombination coefficient increases.

We also examined the quantity $\alpha x^2 n^2$, where $x$ is the ionization fraction of the gas, which removes the assumption of a 100% ionization fraction. In this case, we see the opposite trend and the recombination rate drops from $5 \times 10^{-8}$ to $2 \times 10^{-13} \text{ cm}^{-3} \text{s}^{-1}$. Despite the increase in density and the recombination coefficient, the recombination rates decrease significantly due to the low ionization fraction of the gas after the HII region collapses.

We find that $n^2$ increases by a factor of $\sim 1.5–4$ along the lines of sight within a 1 pc radius of the cluster’s location. This increased density limits the amount of radiation that propagates to larger radii. The gas can then recombine and cool from $\sim 10^4$ K, typical of HII regions, to $\sim 10$ K, which is the temperature floor adopted in the simulation.

This can be visualized by examining the neutral column density from the luminous cluster through the HII region, as shown in Figure 4. The top panels show a slice of density (left) and ionization fraction (right) centered on the luminous cluster associated with the HII region that collapses at 3.25 Myr. These images are plotted before the HII region collapses. At this time, the cluster is no longer deeply embedded in the massive cold filament out of which it formed in the first place. The bottom panels of Figure 4 show a Hammer projection of

---

**Figure 3.** 3D images of the density (green) and ionized regions (red) at 3.18, 3.31, and 3.75 Myr from left to right, respectively. These images correspond to the first peak in $f_{\text{esc}}$ in Figure 2, the trough at 3.31 Myr, and the second peak at 3.75 Myr. The density contours represent densities of $\sim 30 \text{ cm}^{-3}$, and the box side length is 80 pc.
the neutral gas column density across a spherical surface of radius 20 pc centered on the same cluster before the H II region collapses (left) and after the collapse (right). A 20 pc radius circle is shown in the density and ionization fraction slices for reference. The column density projections clearly show that the region that was previously ionized has increased in column density after the H II region collapses.

The increase in density surrounding the massive cluster can be understood through turbulent shocks in the surrounding ionized gas. We measured the local gas velocity dispersion at the location of the cluster immediately before the H II region collapse to be 10.1 km s\(^{-1}\) (corresponding to a Mach number of 1.14). Thus, a density fluctuation can cross the cluster’s radius of 0.78 pc in \(\sim 76,000\) yr. This is comparable to the \(\sim 35,000\) yr it takes for the H II region to collapse. A passing shock could therefore lead to a local density enhancement, causing the H II region to collapse in the observed time. As the gas recombines, it cools and shields regions further along the line of sight.

This further analysis supports our claim that the dynamic nature of the gas, which at this point in time causes the density to increase within the H II region, is responsible for the strong fluctuations in the size of the H II regions being produced by luminous clusters, and hence in the value of \(f_{\text{esc}}\).

The above discussion has focused on \(f_{\text{esc}}\) from the entire molecular cloud, which is a useful quantity when studying the buildup of the ISRF or estimating the global escape fraction from a galaxy as a whole. We may instead investigate the escape fraction from smaller regions surrounding luminous clusters to follow the evolution of \(f_{\text{esc}}\) as a function of distance from the cluster. We are limited in this regard due to the fact that the ray tracer used to compute the radiative transfer only tracks the total flux in each grid cell with no directional information about the incoming rays. This means that if we calculate the flux across a small spherical surface centered on a luminous cluster, it will likely include contributions from sources outside the sphere.

Still, we can calculate \(f_{\text{esc}}\) across a surface if the majority of the total ionizing luminosity is being generated within its volume. This minimizes the contribution to the total flux from outside sources. We find that the 10 most luminous clusters generate 90% of the total ionizing luminosity and are located a maximum of 24.3 pc from the simulation center. We therefore repeat the \(f_{\text{esc}}\) calculation for a sphere of radius 25 pc instead of 33.8 pc, which was presented in Figure 2.

For reference, we show a two-dimensional projection of the position of all clusters in the left panel of Figure 5. The 10 most
luminous clusters are shown by the stars, and all clusters are colored by their Z-position in the cloud. We only show the positions at one time, 3.18 Myr, which corresponds to the first peak of $f_{esc}$ in Figure 2, to illustrate that the clusters are not strongly grouped together but instead cover the cloud’s entire extent.

The right panel of Figure 5 shows $f_{esc}$ across a spherical surface of radius 25 pc. Comparing to the top left panel of Figure 2, we see that $f_{esc}$ across the smaller surface well within the cloud has a similar temporal evolution with pronounced peaks at 3.25 and 3.75 Myr, but the values are $\sim$2 times larger. The average $f_{esc}$ from 2.5 to 4.2 Myr is 41%, compared to 15% for ionizing radiation that escapes from the surface of the cloud. The early evolution (i.e., less than 2.5 Myr) of $f_{esc}$ is also significantly enhanced, likely due to the generation of small H II regions surrounding the luminous clusters that are not large enough to extend to the edge of the simulation volume.

Overall, these results suggest that $f_{esc}$ decreases with cloud radius as one moves through the cloud and out its surface. This trend has been found observationally by Pellegrini et al. (2012), who noted that the global $f_{esc}$ from the LMC and SMC is estimated to be 4% and 11%, respectively, while $f_{esc}$ from individual star-forming regions can be as high as $\sim$60%.

The values presented in Figure 2 are particularly important for the global ISRF and ISM structure since they represent the escape fraction from the surface of an entire $10^6 M_\odot$ GMC. Clouds of this mass are host to the most massive stellar clusters, which dominate the stellar feedback and overall luminosity of a galaxy (Harris & Pudritz 1994; Mac Low & Klessen 2004; McKee & Ostriker 2007; Klessen & Glover 2016).

4. DISCUSSION AND CONCLUSIONS

We computed the UV photon escape fraction from a turbulent, $10^6 M_\odot$ GMC using the astrophysical code FLASH. The cloud, taken from Howard et al. (2016), is initially unbound with a virial parameter of 3, and sink particles are used to model the formation of star clusters. Our simulations end just before supernova explosions could disrupt the star clusters and remove surrounding gas.

Our analysis indicates that the flux is both highly anisotropic, due to the filamentary and clumpy nature of the intervening turbulent gas, and highly variable in time. As time progresses, the flux naturally increases since the clusters contain more massive stars.

The integrated escape fraction, defined as the total number of photons leaving the cloud divided by the total number of photons being produced by all clusters, also varies significantly over time. For the first 2.5 Myr of evolution, $f_{esc}$ remains low at $\sim$5%. There are two distinct peaks in the escape fraction at 3.25 and 3.8 Myr, with a maximum escape fraction of 30% and 37% at the two peaks. The average $f_{esc}$ from the onset of large H II regions at 2.5 Myr to the end of the simulation is 15%. The average $f_{esc}$ increases to 41% if we instead consider a smaller surface well inside the cloud at a radius of 25 pc, as compared to the GMC’s surface, which is at a radius of 33.8 pc.

The peaks of $f_{esc}$ and subsequent troughs are tied to the local gas density structure surrounding the luminous clusters, which determines the size of the H II region they produce. At a peak, the H II is large and extends toward the boundary of the simulation volume. At a trough, the H II region is only a small fraction of its previous size. The collapse of the H II region is tied to the turbulent nature of the gas surrounding the luminous clusters, which causes the density to vary with time. As it increases, so do the recombination rates, and the H II regions shrink.

We argue that calculations of the photon escape fraction on galactic scales require knowledge of $f_{esc}$ for individual GMCs and for the star-forming complexes in their interior. For many applications (e.g., cosmic reionization), this is computationally prohibitive, and we suggest to use an average value of $f_{esc} = 15\%$ for a $10^6 M_\odot$ GMC with fluctuations of a factor of two superimposed on timescales of about 1 Myr.

We thank Bill Harris and Eric Pellegrini for interesting discussions.

C.S.H. and R.E.P. thank the the Zentrum für Astronomie der Universität Heidelberg (ZAH), Institut für Theoretische
Astrophysik (ITA), and the Max-Planck-Institut für Astronomie (MPIA), for their generous support during R.E.P.’s sabbatical leave (2015/16) and C.S.H.’s extended visit (2015 October–November).

R.E.P. is supported by Discovery Grants from the Natural Sciences and Engineering Research Council (NSERC) of Canada. C.S.H. acknowledges financial support provided by the Natural Sciences and Engineering Research Council (NSERC) through a postgraduate scholarship. The FLASH code was in part developed by the DOE-supported Alliances Center for Astrophysical Thermonuclear Flashes (ASCI) at the University of Chicago. This work was made possible by the facilities of the Shared Hierarchical Academic Research Computing Network (SHARCNET: www.sharcnet.ca) and Compute/Calcul Canada.

R.S.K. acknowledges support from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) via the ERC Advanced Grant “STARLIGHT: Formation of the First Stars” (project no. 339177). R.S.K. further acknowledges funding from the Deutsche Forschungsgemeinschaft (DFG) in the Collaborative Research Center SFB 881 The Milky Way System (subprojects B1, B2, and B8) and in the Priority Program SPP 1573 Physics of the Interstellar Medium (grant nos. KL 1358/18.1 and KL 1358/19.2).

REFERENCES

André, P., Di Francesco, J., Ward-Thompson, D., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tuscon, AZ: Univ. Arizona Press)
Banerjee, R., Pudritz, R. E., & Anderson, D. W. 2006, MNRAS, 373, 1091
Bate, M. R. 2012, MNRAS, 419, 3115
Bertoldi, F., & McKee, C. F. 1992, ApJ, 395, 140
Bertoldi, F., & McKee, C. F. 1992, ApJ, 395, 140
Chabrier, G. 2005, in The Initial Mass Function 50 Years Later, Astrophysics and Space Science Library Vol. 327 (Dordrecht: Springer), 41
Dale, J. E., Bonnell, I. A., Clarke, C. J., & Bate, M. R. 2005, MNRAS, 358, 291
De Pree, C. G., Peters, T., Mac Low, M.-M., et al. 2014, ApJL, 781, L36
De Pree, C. G., Peters, T., Mac Low, M.-M., et al. 2015, ApJ, 815, 123
Draine, B. T. 1978, ApJS, 36, 595
Draine, B. T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, NJ: Princeton Univ. Press)
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Federrath, C., Banerjee, R., Clark, P. C., & Klessen, R. S. 2010, ApJ, 713, 269
Ferrara, A., & Loeb, A. 2013, MNRAS, 431, 2826
Frank, A., & Mellema, G. 1994, A&A, 289, 937
Fryxell, B., Olson, K., Ricker, P., et al. 2000, ApJS, 131, 273
Galván-Madrid, R., Peters, T., Keto, E. R., et al. 2011, MNRAS, 416, 1033
Girichidis, P., Federrath, C., Banerjee, R., & Klessen, R. S. 2011, MNRAS, 413, 2741
Goldsmith, P. F. 2001, ApJ, 557, 736
Habing, H. J. 1968, BAN, 19, 421
Harris, W. E., & Pudritz, R. E. 1994, ApJ, 429, 177
Howard, C. S., Pudritz, R. E., & Harris, W. E. 2014, MNRAS, 438, 1305
Howard, C. S., Pudritz, R. E., & Harris, W. E. 2016, MNRAS, 461, 2953
Klessen, M., Peters, T., & Pudritz, R. 2012a, ApJ, 758, 137
Klessen, M., Pudritz, R. E., & Peters, T. 2012b, MNRAS, 421, 2861
Klessen, R. S., & Glover, S. C. O. 2016, Saas Fee Lecture Notes, 43, 85
Klessen, R. S., & Hennebelle, P. 2010, A&A, 520, A17
Krumholz, M. J., Cunningham, A. J., Klein, R. I., & McKee, C. F. 2010, ApJ, 713, 1120
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Li, A., & Draine, B. T. 2001, ApJ, 554, 778
Mac Low, M.-M., & Klessen, R. S. 2004, RevMP, 76, 125
Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, A&A, 128, 212
McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
Mellema, G., & Lundqvist, P. 2002, A&A, 394, 901
Murray, N., Quataert, E., & Thompson, T. A. 2010, ApJ, 709, 191
Nestor, D. B., Shapley, A. E., Kornei, K. A., Steidel, C. C., & Siana, B. 2013, ApJ, 765, 47
Neufeld, D. A., Lepp, S., & Melnick, G. J. 1995, ApJS, 100, 132
Paardekooper, J. P., Khochfar, S., & Dalla Vecchia, C. 2015, MNRAS, 429, 2544
Paardekooper, J. P., Pelupessy, F. I., Altay, G., & Kroupa, P. 2011, A&A, 530, A87
Pellegrini, E. W., Oey, M. S., Winkler, P. F., et al. 2012, ApJ, 755, 40
Peters, T., Banerjee, R., Klessen, R. S., et al. 2010a, ApJ, 711, 1017
Peters, T., Mac Low, M.-M., Banerjee, R., Klessen, R. S., & Dullemond, C. P. 2010b, ApJ, 719, 831
Pollack, J. B., Hollenbach, D., Beckwith, S., et al. 1994, ApJ, 421, 615
Razoumov, A. O., & Sommer-Larsen, J. 2010, ApJ, 710, 1239
Rijkhorst, E. J., Plewa, T., Dubey, A., & Mellema, G. 2006, A&A, 452, 907
Robertson, B. E., Ellis, R., Dunlop, J., McLure, R., & Stark, D. 2010, Natur, 468, 55
Robertson, B. E., Furlanetto, S. R., Schneider, E., et al. 2013, ApJ, 768, 71
Siana, B., Shapley, A. E., Kulas, K. R., et al. 2015, ApJ, 804, 17
Tout, C. A., Pols, O. R., Eggleton, P. P., & Han, Z. 1996, MNRAS, 281, 257
Walch, S., Whitworth, A. P., Bisbas, T. G., Wünsch, R., & Hubber, D. A. 2013, MNRAS, 435, 917
Wise, J. H., Demchenko, V. G., Halicek, M. T., et al. 2014, MNRAS, 442, 2560
Xu, H., Wise, J. H., Norman, M. L., Ahn, K., & O’Shea, B. W. 2015, arXiv:1604.07842