Outflows Driven by Direct and Reprocessed Radiation Pressure in Massive Star Clusters

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ABSTRACT
We use three-dimensional radiation hydrodynamic (RHD) simulations to study the formation of massive star clusters under the combined effects of direct ultraviolet (UV) and dust-reprocessed infrared (IR) radiation pressure. We explore a broad range of mass surface density $\Sigma \sim 10^2$–$10^3$ $M_\odot$ pc$^{-2}$, spanning values typical of weakly star-forming galaxies to extreme systems such as clouds forming super-star clusters, where radiation pressure is expected to be the dominant feedback mechanism. We find that star formation can only be regulated by radiation pressure for $\Sigma \lesssim 10^3$ $M_\odot$ pc$^{-2}$, but that clouds with $\Sigma \lesssim 10^5$ $M_\odot$ pc$^{-2}$ become super-Eddington once high star formation efficiencies ($\gtrsim 80\%$) are reached, and therefore launch the remaining gas in a steady outflow. These outflows achieve mass-weighted radial velocities of $\sim 15$–$30$ km s$^{-1}$, which is $\sim 0.5$–$2.0$ times the cloud escape speed. This suggests that radiation pressure is a strong candidate to explain recently observed molecular outflows found in young super-star clusters in nearby starburst galaxies. We quantify the relative importance of UV and IR radiation pressure in different regimes, and deduce that both are equally important for $\Sigma \sim 10^3$ $M_\odot$ pc$^{-2}$, whereas clouds with higher (lower) density are increasingly dominated by the IR (UV) component. Comparison with control runs without either the UV or IR bands suggests that the outflows are primarily driven by the impulse provided by the UV component, while IR radiation has the effect of rendering a larger fraction of gas super-Eddington, and thereby increasing the outflow mass flux by a factor of $\sim 2$.

Key words: ISM: clouds – HII regions – radiation: dynamics – methods: numerical – stars: formation – radiative transfer

1 INTRODUCTION
Radiation pressure on dust grains is a potentially important mechanism in regulating star formation and disrupting dusty gas in star clusters (Krumholz & Matzner 2009; Fall et al. 2010; Murray et al. 2010; Raskutti et al. 2016; Thompson & Krumholz 2016; Raskutti et al. 2017), maintaining the vertical stability of starbursts and AGN discs (Scoville 2003; Thompson et al. 2005; Andrews & Thompson 2011; Krumholz & Thompson 2012), and launching winds from galaxies, Active Galactic Nuclei (AGN), star clusters, young massive stars, and evolved asymptotic giant branch (AGB) stars (Murray et al. 2011; Roth et al. 2012; Krumholz & Thompson 2013; Davis et al. 2014; Thompson et al. 2015; Rosen et al. 2016; Wikking et al. 2018; Zhang 2018; Costa et al. 2018; Höfner & Olofsson 2018). In the context of star/cluster formation, radiation pressure provides a crucial contribution in the expansion of feedback-driven H ii regions/bubbles (Draine 2011; Kim et al. 2016), which limit the integrated star formation efficiency ($\epsilon_s$) of giant molecular clouds (GMCs) and lead to their inferred short lifetimes (Chevance et al. 2020, 2022a,b).

The mechanism of radiation pressure operates through the absorption of momentum in photons by dust grains, and coupling this momentum to the gas through collisions. Photons in two broad frequency bands are relevant here: the direct UV/optical photons from young stars, and the dust-reprocessed IR photons. The opacity of dust grains to the former is typically $\kappa_{UV} \sim 100$–$1000$ cm$^2$ g$^{-1}$, and thereby clouds with surface densities $\Sigma \gtrsim \kappa_{UV}^{-1} \sim 10$–$100$ $M_\odot$ pc$^{-2}$ are optically thick to these photons, and therefore susceptible to dispersal by direct radiation pressure. That being said, the thermal pressure of photoionised gas can be comparable to or larger than radiation pressure in some range of $\Sigma$; indeed, semi-analytic models (Krumholz & Matzner 2009; Fall et al. 2010; Murray et al. 2010; Kim et al. 2016; Rahner et al. 2017), numerical simulations (Kim et al. 2018), and observations (Lopez et al. 2011, 2014; Barnes et al. 2020; Olivier et al. 2021) find that radiation pressure is the dominant feedback mechanism only for clouds whose escape velocities are $\gtrsim 10$ km s$^{-1}$. Such conditions are realised in GMCs that go on to form young massive star clusters (Portegies Zwart et al. 2010). On the other hand, the IR opacities of dust are significantly lower ($\kappa_{IR} \lesssim 10$ cm$^2$ g$^{-1}$; Semenov et al. 2003), and therefore require much higher cloud surface densities ($\Sigma \gtrsim 10^3$ $M_\odot$ pc$^{-2}$) to effectively absorb these photons. However, if this condition is satisfied, IR photons can undergo repeated cycles of absorption and emission, enhancing the imparted momentum over the stellar UV/optical photon momentum (Thompson et al. 2005; Murray et al. 2010). This is the so-called multiple-scattering regime, to differentiate it from the single-scattering regime, where the dust is optically thin to IR photons. Environments in the multiple-scattering regime in the local universe are primarily found in extreme regions such as dwarf starbursts and ultra-luminous infrared galaxies (ULIRGs) like Arp 220,
which are subject to high external pressures \( (P/k_B \geq 10^8 \text{ K cm}^{-3}) \). These environments potentially host the formation sites of super-star clusters (SSCs; e.g., McCrady et al. 2005; Portegies Zwart et al. 2010; Turner et al. 2015; Smith et al. 2020), and represent a dense mode of star formation that might have existed more commonly at high redshift. Observations suggest that these clusters form stars very efficiently and are mostly bound, with the role of stellar feedback on their formation and evolution largely uncertain (Turner et al. 2017; Smith et al. 2020; Emig et al. 2020; Rico-Villase et al. 2020; Costa et al. 2021; He et al. 2022).

Recently, observations using the Atacama Large Millimeter/Submillimeter Array (ALMA) have managed to study the young, embedded phase of SSC formation at high resolution (~ 2 pc) in the nearby dwarf starburst NGC 253, shedding light on the properties of their natal GMCs (Leroy et al. 2018), and the young stellar populations in them (Mills et al. 2021). Levy et al. (2021) conducted follow-up observations at even higher resolution (~ 0.5 pc) that have managed to probe the cluster-scale kinematics and feedback in these SSCs. Intriguingly, they find evidence of massive outflows from 3 of the 14 SSCs they characterise, with outflow velocities comparable to the UV could increase the contribution of radiation pressure in the UV band, and focused solely on the possibility that radiation pressure could drive the sort of winds seen in NGC 253. However, these simulations did not consider the UV contribution of the direct and reprocessed radiation pressure in the IR, and the dominant forces (UV vs IR) driving these outflows.

In Section 4 we provide a summary of our results, and discuss them in the context of the observed outflows in NGC 253.

2 METHODS

The simulation setup in this study largely follows that of Paper I; therefore, we summarize the salient features of our setup below and refer the reader to Section 2 of Paper I for further details.

2.1 Equations solved

We solve the non-relativistic RHD equations in two grey bands that represent the stellar UV and dust-reprocessed IR bands respectively, self-consistently computing the reprocessing of the UV to the IR by dust. We use the mixed-frame formulation (Mihalas & Klein 1982) in the RHD equations, retaining terms that are of leading order in all limiting regimes of RHD (see, e.g., Krumholz et al. 2007), given by

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]  
\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P + \rho \nabla \Phi + G_{\text{UV}} + G_{\text{IR}} \]  
\[ \frac{\partial E_{\text{r,UV}}}{\partial t} + \nabla \cdot (\mathbf{F}_{\text{r,UV}}) = j_s - c c E_{\text{r,UV}} \]  
\[ \frac{\partial E_{\text{r,IR}}}{\partial t} + \nabla \cdot (c^2 \mathbf{P}_{\text{r,IR}}) = -c^2 G_{\text{r,IR}} \]

where,

\[ G_{\text{r,UV}} = \rho x (c^2 - \kappa_{\text{r,UV}}) \left[ \frac{\mathbf{P}}{c^2} \right] \]

\[ G_{\text{r,IR}} = \rho x (c^2 - \kappa_{\text{r,IR}}) \left[ \frac{\mathbf{P}}{c^2} \right] \]

and \( \kappa \equiv (\text{UV}, \text{IR}) \) represent the band evolved in a corresponding equation. In the above equations \( \rho \) is the mass density, \( P \) the gas thermal pressure, \( \mathbf{v} \) the gas velocity, \( \Phi \) the gravitational potential, \( I \) the identity matrix, and \( c \) the speed of light in vacuum. In the radiation moment equations (Equations 3 – 6), \( E_{\text{r,UV}} \) is the lab-frame radiation energy density, \( F_{\text{r}} \) the lab-frame radiation momentum density, \( \mathbf{P} \) the lab-frame radiation pressure tensor, \( \kappa_{\text{UV}} \) and \( \kappa_{\text{IR}} \) are the Planck

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]  
\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P + \rho \nabla \Phi + G_{\text{UV}} + G_{\text{IR}} \]  
\[ \frac{\partial E_{\text{r,UV}}}{\partial t} + \nabla \cdot (\mathbf{F}_{\text{r,UV}}) = j_s - c c E_{\text{r,UV}} \]  
\[ \frac{\partial E_{\text{r,IR}}}{\partial t} + \nabla \cdot (c^2 \mathbf{P}_{\text{r,IR}}) = -c^2 G_{\text{r,IR}} \]

3 Note that we denote tensor contractions over a single index with dots (e.g., \( a \cdot b \)), tensor contractions over two indices by colons (e.g., \( A:B \)), and tensor products of vectors without an operator symbol (e.g., \( a b \)).
and Rosseland mean opacities with averages computed over the IR and UV bands\(^4\). \(j_r\) represents the direct UV radiation contribution rate from sink particles (Federrath et al. 2010b; Menon et al. 2022a) and \(j_s\) represents the solid-angle integrated diffuse emission due to dust grains in the given band. Equation 7 is the closure relation for the gas pressure, for which we assume an isothermal equation of state in our simulations, i.e., \(P = \rho c_s^2\), where \(c_s\) is the thermal sound speed of the gas. The assumption of an isothermal equation of state does not considerably affect our results as the thermal pressure is subdominant over the radiation pressure in our simulations, and plays a minor role in the dynamics of our clouds. What would be affected by this assumption is the fragmentation on small scales. Heating by accretion feedback suppresses fragmentation (Offner et al. 2009; Bate 2009; Krumholz et al. 2016; Federrath et al. 2017; Guszejnov et al. 2018; Mathew & Federrath 2020), but our current simulations do not resolve these small-scale fragmentation processes anyway. What matters for the present simulations is the radiation output from massive stars and sub-clusters, which is modelled by sampling from a standard initial mass function on un-resolved scales, i.e., our sink particles represent small star clusters rather than individual stars (for details, see Paper I).

We pause to explain the radiation energy source terms on the right-hand side of Equations 3 and 5. In Equation 3, the term \(j_s\) represents the UV photons emitted by the sink particles. We set the diffuse emission term \(j_{s,UV} = 0\), as the dust does not re-emit in the UV. In Equation 5, the first term represents the contribution to the dust-reprocessed IR radiation under the (very reasonable) assumption that all the energy the dust has absorbed from UV photons is instantly reprocessed into the IR\(^5\). This treatment of the IR radiation field is more consistent than the approach in Paper I where IR photons are injected directly with a term analogous to \(j_s\). For the diffuse emission, we set \(j_{s,IR} = a_g T^4\), where \(a_g\) is the radiation constant, to represent the emission in the IR by dust grains. We also invoke the assumption of radiative equilibrium for the IR radiation – i.e., the dust temperature is always equal to the radiation temperature \(T_r = \langle E_r,IR / a_g \rangle^{1/4}\). This assumption is justified in Appendix A of Krumholz & Thompson (2013) considering the regime we are studying\(^6\). The combination of the aforementioned assumptions implies that the first term in the parentheses in Equation 8 for the IR band is zero, and therefore net heating or cooling from IR radiation arises purely due to mechanical contributions.

To close the equations above, we require a closure relation for the radiation pressure tensor. In both bands, we adopt the variable Eddington tensor (VET) closure

\[
P_{r,t} = T_4 E_{r,t},
\]

where \(T_4\) is the Eddington Tensor for a given band. We use an Eddington tensor directly calculated from angular quadratures of the band specific intensity \(I_{r,t}(\hat{n}_k)\), using the relations

\[
E_{r,t} = \int d\Omega I_{r,t}(\hat{n}_k)/c,
\]

\[
P_{r,t} = \int d\hat{n}_k \hat{n}_k I_{r,t}(\hat{n}_k)/c.
\]

\(I_{r,UV}\) and \(I_{r,IR}\) are calculated from formal solutions of the time-independent radiative transfer equations in the respective bands,

\[
\frac{dI_{r,UV}}{ds} = \frac{j_s}{4\pi} - \rho \kappa_{R,UV} I_{r,UV}
\]

\[
\frac{dI_{r,IR}}{ds} = \rho \kappa_{IR} \left[ \frac{c j_{IR}}{4\pi} - I_{r,IR} \right]
\]

where the term \(j_s/(4\pi)\) represents the photons from the isotropically emitting sink particle, and \(j_{IR}\) is the frequency-integrated reprocessed emission of the dust grain at the temperature \(T_r\), which is also assumed to be directionally isotropic. We use the grey Rosseland-mean opacity, \(\kappa_{R,IR}\) (\(\kappa_{IR}\)) in Equation 13 (14) to ensure consistency with the choice of flux-mean opacity we made in the radiation moment equations.

2.2 Numerical methods

The numerical methods used to solve the equations outlined in the previous section are identical to Menon et al. (2022a). We use the Variable Eddington Tensor-closed Transport on Adaptive Meshes (VETTAM; Menon et al. 2022b) method coupled to the FLASH magneto-hydrodynamics code (Fryxell et al. 2000; Dubey et al. 2008) for our simulations. For the hydrodynamic updates, we use an explicit Godunov method in the split, five-wave HLLSR (approximate) Riemann solver (Waagan et al. 2011). The Poisson equation for the self-gravity is solved using a multi-grid algorithm implemented in FLASH (Ricker 2008). Sink particles are used to follow the evolution of gas at unresolved scales, the formation of which is triggered when gas properties satisfy a series of conditions to test for collapse and star formation (Federrath et al. 2010b). Gravitational interactions of sink particles with gas and other sinks are considered, and a second-order leapfrog integrator is used to advance the sink particles (Federrath et al. 2010b, 2011).

Sink particles in our simulations represent unresolved sub-clusters rather than individual stars. As in Paper I, we assume that these sub-clusters fully sample the initial mass function (IMF) of a young stellar population, and adopt an appropriate fixed light-to-mass ratio of \((L_*/M_*) = 1.7 \times 10^3\) erg s\(^{-1}\) g\(^{-1}\), where \(M_*\) is the mass of the radiating source. The UV radiation from sink particles is then included via the term \(j_s\) in Equation 3, given by

\[
j_s(r) = \frac{L_*/(2\pi r_a^2)^{3/2}}{3\pi} \exp \left( -\frac{r^2}{2\sigma_r^2} \right)
\]

where \(L_* = M_* (L_*/M_*)\), and \(r\) is the radial distance of a grid cell from the sink particle. We adopt a value of \(\sigma_r = 4\Delta x_{\text{min}}\), where \(\Delta x_{\text{min}}\) is the minimum cell size in the domain; we have shown in Paper I that the radiation forces are fairly insensitive to the choice of this parameter.

The radiation moment equations in the UV (Equations 3 and 4) and
IR (Equations 5 and 6) bands are operator-split from the hydromagnetic and gravity updates, and solved with an implicit Euler-backward temporal scheme (Menon et al. 2022b). We perform two radiation updates per hydrodynamic timestep: first for the UV band, then followed by the IR band, which uses the time-updated solution in the UV band as a source term (i.e., the first term on the RHS of Equation 5) - hence the scheme is fully implicit in the radiation quantities\(^7\). The time-independent radiative transfer equations (Eq. 13 and 14) for obtaining the VET closure are obtained with a hybrid characteristics ray-tracing scheme (Buntemeyer et al. 2016a), and is computed prior to the radiation moment update for the respective band.

In Paper I we performed a series of tests with VETTAM to quantify the accuracy of our VET-based RHD scheme for IR radiation. Since here is the first time that VETTAM is utilised to model UV radiation pressure, we reproduce the results obtained with our scheme for the fiducial model of Raskutti et al. (2016) in Appendix A. Kim et al. (2017) to demonstrate that the algorithm introduced by Rosen et al. (2016) underestimates the (UV) radiation forces, and as a result, the net star formation efficiency (\(\epsilon_{\text{sf}}\)) - obtaining \(\epsilon_{\text{sf}} \sim 25\%\) with the ART scheme as opposed to ~ 42% in the Raskutti et al. (2016) version. We find a value of \(\epsilon_{\text{sf}} \sim 28\%\), which is closer to the ART result than the \(M_1\), demonstrating that a moment method based on the VET closure can be of comparable accuracy to an ART scheme for modelling the dynamical effects of streaming radiation forces\(^8\).

\(^7\) An alternate approach to treat the coupled nature of the two bands is to solve Equations (3)–(6) together in one global, implicit update for both bands. However, we found that the resulting performance and accuracy with this approach was inferior to the one we adopt. This is likely due to the fact that in a global update, the coupling between UV and IR bands has to be treated \textit{internally} in the solution of the linear system, and thus the equality of the energy lost to the UV band and gained by the IR band is enforced only to the level imposed by the linear solver tolerance. By contrast, in our two-step process we can guarantee the equality of these quantities to machine precision. A subtle point worth noting here is that our adopted approach is possible only because the coupling between the bands is unidirectional in frequency space – i.e., from UV to IR. For a system where this is not the case, a single, coupled update would be required.

\(^8\) It is important to point out however, that an ART scheme, while quite accurate for streaming radiation, would be unable to model reprocessed or diffuse radiation (i.e., the IR band).

### 2.3 Initial conditions and parameters

We initialise our simulations as a uniform spherical cloud with mass \(M_{\text{cloud}}\) and radius \(R_{\text{cloud}}\), which together define a cloud mass density \(\rho_{\text{cloud}} = M_{\text{cloud}}/(4/3\pi R_{\text{cloud}}^3)\) and a mass surface density \(\Sigma_{\text{cloud}} = M_{\text{cloud}}/(\pi R_{\text{cloud}}^2)\). The clouds are placed in a lower-density ambient medium with \(\rho = \rho_{\text{cloud}}/100\) in pressure-equilibrium, achieved using a mass-scalar to represent cloud material (see Section 2.4 of Paper I). The domain size is fixed to \(L = 4R_{\text{cloud}}\) to allow sufficient volume to track potentially expanding material due to feedback. Clouds are initialised with turbulent velocities that follow a power spectrum \(E(k) \sim k^{-2}\) with a natural mixture of solenoidal and compressive modes (appropriate for supersonic molecular-cloud turbulence; see e.g., Heyer & Brunt 2004; Federrath 2013) for \(k/(2\pi L) \in [2, 64]\), generated with the methods described in Federrath et al. (2010a), and publicly available (Federrath et al. 2022). The velocity dispersion \(\sigma_v\) is set such that the virial parameter \(\alpha_v = 2\) where \(\alpha_v\) is given by

\[
\alpha_v = \frac{2E_{\text{kin}}}{E_{\text{grav}}} = \frac{5R_{\text{cloud}}^2}{3GM_{\text{cloud}}}.
\]

where \(E_{\text{kin}} = (1/2)M_{\text{cloud}}\sigma_v^2\) and \(E_{\text{grav}} = (3/5)GM_{\text{cloud}}^2/R_{\text{cloud}}\). The sound speed \(c_s\) is set such that the sonic Mach number \(M = \sigma_v/c_s = 11.5\). Our choice of \(\alpha_v\) ensures the cloud is marginally bound in its initial state; we do not explore variations of \(\alpha_v\) since we found relatively minor differences in the competition between radiation and gravity in Paper I (Section 3.2.3) with different \(\alpha_v\). We also do not include magnetic fields in our simulations; we discuss in Paper I the caveats associated with this. The domain boundary conditions for the hydrodynamics are set to diode – i.e., gas is allowed to flow out of the domain, but not allowed to enter it.

The opacity in the UV band is set to a constant value of \(\kappa_{\text{UV}} = \kappa_{\text{UV}} = 1000\, \text{cm}^2\, \text{g}^{-1}\), consistent with typical estimates of the gray radiation pressure cross section per H atom to blackbody radiation peaking at UV wavelengths (blackbody temperatures ~ few \(\times 10^4\) K; Draine 2011). The opacity in the IR band is kept identical to Paper I, i.e., a temperature- and density-dependent infrared opacity with \(\kappa_{\text{IR}} = 0\) (due to radiative equilibrium) and \(\kappa_{\text{IR}} = \kappa_{\text{Sem}}\), where \(\kappa_{\text{Sem}} = \kappa_{\text{Sem}}(\rho, T_e)\) is the Semenov et al. (2003) opacity, calculated at the radiation temperature \(T_e\). The temperature dependence of the opacity in the IR is retained, which is crucial to accurately capture the dynamics of the clouds under reprocessed radiation pressure (Paper

| Model | \(M_{\text{cloud}}\) [\(10^6\, \text{M}_\odot\)] | \(R_{\text{cloud}}\) [pc] | \(\Sigma_{\text{cloud}}\) [\(\text{M}_\odot\, \text{pc}^{-2}\)] | \(n_{\text{cloud}}\) [\(\text{cm}^{-3}\)] | \(\sigma_v\) [km/s] | \(v_{\text{esc}}\) [km/s] | \(t_{\text{ff}}\) [Myr] | UV | IR |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|---|---|
| S2UVIR | 1.0 | 31.5 | 3.2\times10^2 | 3.1\times10^2 | 12 | 16 | 3.0 | ✓ | ✓ |
| S3UVIR | 1.0 | 10.0 | 3.2\times10^3 | 9.7\times10^3 | 22 | 29 | 0.5 | ✓ | ✓ |
| S4UVIR | 1.0 | 3.2 | 3.2\times10^4 | 3.1\times10^5 | 40 | 52 | 0.09 | ✓ | ✓ |
| S5UVIR | 1.0 | 1.0 | 3.2\times10^5 | 9.7\times10^6 | 71 | 92 | 0.02 | ✓ | ✓ |
| S2U | 1.0 | 31.5 | 3.2\times10^2 | 3.1\times10^2 | 12 | 16 | 3.0 | ✓ | ✓ |
| S3U | 1.0 | 10.0 | 3.2\times10^3 | 9.7\times10^3 | 22 | 29 | 0.5 | ✓ | ✓ |
| S4U | 1.0 | 3.2 | 3.2\times10^4 | 3.1\times10^5 | 40 | 52 | 0.09 | ✓ | ✓ |
| S3IR | 1.0 | 10.0 | 3.2\times10^3 | 9.7\times10^3 | 22 | 29 | 0.5 | ✓ | ✓ |
| S4IR | 1.0 | 3.2 | 3.2\times10^4 | 3.1\times10^5 | 40 | 52 | 0.09 | ✓ | ✓ |
| S5IR | 1.0 | 1.0 | 3.2\times10^5 | 9.7\times10^6 | 71 | 92 | 0.02 | ✓ | ✓ |

Notes: The row in bold denotes the fiducial simulation of our study. Columns in order indicate - Model: model name, \(M_{\text{cloud}}\): mass of cloud, \(R_{\text{cloud}}\): radius of cloud, \(\Sigma_{\text{cloud}}\): mass surface density of the cloud given by \(\Sigma_{\text{cloud}} = M_{\text{cloud}}/(\pi R_{\text{cloud}}^2)\), \(n_{\text{cloud}}\): number density of the cloud given by \(n_{\text{cloud}} = 3M_{\text{cloud}}/(4\pi R_{\text{cloud}}^3)\pi\), where \(m_H\) is the mass of atomic hydrogen, \(\sigma_v\): turbulent velocity dispersion of the cloud, \(v_{\text{esc}}\): escape velocity of the cloud, \(t_{\text{ff}}\): free-fall time of the cloud, UV: UV band is on (✓) or off (×), IR: IR band is on (✓) or off (×).

Summary of our simulation suite and their initial condition parameters.
The initial condition for the radiation is as follows: \( E_{r, \text{UV}} = F_{\text{UV}} = 0 \), and \( E_{r, \text{IR}} = a_R T_{b,0}^4 \), \( F_{\text{IR}} = 0 \), where \( T_{b,0} = 40 \text{K} \) is the initial dust temperature in the cloud. We adopt Marshak boundary conditions for the radiation field (Marshak 1958), with boundary radiation temperatures of \( T_{b, \text{UV}} = 0 \) and \( T_{b, \text{IR}} = T_{b,0} \) respectively. We also note that the boundary condition for the ray-tracer is kept consistent with these choices.

We note that we do not treat photoionization of gas by UV photons, and the corresponding thermal-pressure driven feedback on the clouds. However, in the regime we are exploring (high surface density clouds with escape speeds \( \gtrsim 10 \text{km/s} \)), radiation pressure forces have been shown to exceed ionized gas pressure, and dominate the dynamical evolution of clouds (Dale et al. 2012; Kim et al. 2016, 2018).

### 2.4 Simulations

We run a range of simulations with different surface densities \( \Sigma_{\text{cloud}} \) – along the lines of Paper I – to test the impact of radiation pressure in different environments. We obtain our target values of \( \Sigma_{\text{cloud}} \) by keeping the mass of the clouds fixed to \( M_{\text{cloud}} = 10^3 \text{M}_\odot \) and scaling \( R_{\text{cloud}} \) appropriately. We test values of \( \Sigma_{\text{cloud}} = 3.2 \times 10^3 \text{M}_\odot \text{pc}^{-2} \) up to \( \Sigma_{\text{cloud}} = 3.2 \times 10^4 \text{M}_\odot \text{pc}^{-2} \), varying by factors of 10 between consecutive runs with different \( \Sigma_{\text{cloud}} \); the resulting cloud parameters are tabulated in Table 1. All of our clouds are optically thick to UV photons. We note that our parameters cover a range that is more massive and of higher surface density than typical star-forming clouds in local galaxies, a choice motivated by the expectation that radiation pressure is the dominant stellar feedback mechanism in this regime (Krumholz & Matzner 2009; Fall et al. 2010; Kim et al. 2016). The two lowest surface density points (\( \Sigma_{\text{cloud}} \sim 10^2-10^3 \text{M}_\odot \text{pc}^{-2} \)) represent conditions appropriate for young massive clusters in regions like the Central Molecular Zone (CMZ), whereas the two higher values of \( \Sigma_{\text{cloud}} \sim 10^4-10^5 \text{M}_\odot \text{pc}^{-2} \) represent super-star clusters that are probably found only in more extreme environments such as starburst galaxies (e.g., Leroy et al. 2018).

Our standard runs evolve radiation in both the UV and IR bands. To isolate the effects of the radiation pressure in either band, and to quantify their relative importance in the evolution of the clouds, we also run some control simulations where either the UV or IR band is not included. We list all the simulations explored in this study in Table 1. The IR-only runs have already been presented in Paper I; the UV-only runs are new. We adopt as a convention that run names are of the form SsUVIR, SsUV, and SsIR respectively for UV+IR, UV-only, and IR-only runs, with \( s \) encoding the cloud surface density \( \Sigma_{\text{cloud}} = 3.2 \times 10^3 \text{M}_\odot \text{pc}^{-2} \). We do not simulate a UV-only version for \( \Sigma_{\text{cloud}} = 3.2 \times 10^4 \text{M}_\odot \text{pc}^{-2} \), as we expect UV to be unimportant compared to IR at these high surface densities; low-resolution tests confirm this is the case. Similarly, we do not run an IR-only version for our lowest surface density case (\( \Sigma_{\text{cloud}} = 3.2 \times 10^3 \text{M}_\odot \text{pc}^{-2} \)), as it is below the typical surface densities required to be optically thick to IR photons (\( \Sigma \lesssim 10^3 \text{M}_\odot \text{pc}^{-2} \)).

All our simulations use a uniform grid (UG) with \( N^3 = 256^3 \) grid cells; for our domain of size \( L = 4R_{\text{cloud}} \), this corresponds to a resolution in terms of the number of grid cells per cloud radius of \( R_{\text{cloud}}/Ax = 64 \). We show that our results are converged with numerical resolution in Appendix B. We adopt a CFL number of 0.4, a relative tolerance of \( 10^{-8} \) for our implicit update of the radiation moment equations, and perform the solution to the time-independent transfer equation with 48 rays per cell using our ray-tracing scheme (based on the Healpix algorithm; Buntemeyer et al. 2016b). We run all simulations up to the point where all the mass has been accreted onto sink particles or expelled from the computational domain by radiation forces, or to a time \( t = 8t_{\text{ff}} \), where \( t_{\text{ff}} \) is the free-fall time of the cloud – whichever is earlier.

### 3 RESULTS

Here we present the main results of our study, beginning with a broad overview of the qualitative outcomes in Section 3.1. We follow this up with a detailed examining of the radiatively-driven outflows we observe in Section 3.2, a comparison of the relative roles of the IR and UV radiation forces in Section 3.3, and a quantitative analysis of the (in)efficiency of radiation in regulating star formation in Section 3.4.

#### 3.1 Evolution of Clouds

We discuss the time evolution of our fiducial set of model clouds in this section. The initial turbulent fluctuations form filamentary structures that become gravitationally unstable, and go on to collapse until sink particles (which represent sub-clusters of stars) form. This introduces radiation pressure due to feedback – i.e., UV photons from the sink particles and the subsequently reprocessed IR photons – which acts as potential support against gravitational collapse. The subsequent dynamics of the clouds are controlled by whether, and at what point, radiation forces are able to compete with gravity, and therefore depend on \( \Sigma_{\text{cloud}} \); this can be seen in Figures 1 and 2, which show snapshots of the gas surface density at times \( t \sim 3t_{\text{ff}} \) and \( t \sim 7t_{\text{ff}} \) respectively, for the different runs. In model S2UVIR (\( \Sigma_{\text{cloud}} = 3.2 \times 10^3 \text{M}_\odot \text{pc}^{-2} \), accretion terminates by \( t \sim 2t_{\text{ff}} \), and radiation forces start driving gas outwards, forming bubbles and filaments characteristic of \( \text{H}_2 \) regions, and evacuating gas from the domain (top-left panel in Figure 1). Eventually, by \( t \sim 4-5t_{\text{ff}} \), all the gas is evacuated from the domain, and only the sink particles remain (top-left panel in Figure 2). Model S3UVIR continues to accrete gas even beyond \( t \gtrsim 2t_{\text{ff}} \), and accumulates more mass in sink particles than S2UVIR; however by \( t \sim 3t_{\text{ff}} \), radiation forces become stronger than gravity over a large part of the domain, initiating an outflow (top-right panel in Figure 1), which becomes stronger and more extended over time (top-right panel in Figure 2). Model S4UVIR evolves similarly at early times, but unlike the earlier cases, there are no signs of radiation-driven outflows at \( t \sim 3t_{\text{ff}} \); once \( t \sim 6t_{\text{ff}} \), however, an outflow is initiated, albeit less pronounced and more asymmetrical than in the cases with lower \( \Sigma_{\text{cloud}} \) (Figure 2), however showing indications of increasing strength with time. Finally, model S5UVIR continues to collapse for the whole duration of the simulation, with the snapshots showing only signs of infall and rotation (present due to the non-zero angular momentum imparted by the initial turbulent fluctuations), implying that gravity dominates the dynamics in this case.

We quantify the evolutionary stages in the simulations, and the differences with \( \Sigma_{\text{cloud}} \), by measuring the the star formation efficiency \( \epsilon_* \), given by

\[
\epsilon_* = \frac{M_s}{M_{\text{cloud}}},
\]

where \( M_s \) is final stellar mass, and \( M_{\text{cloud}} \) is the initial cloud mass; Figure 3 shows \( \epsilon_* \) (top panel) as a function of time for the different model clouds. We see that the combined gravitational forces from the sink particles and the gas self-gravity increase \( \epsilon_* \) for \( t \leq 2-3t_{\text{ff}} \), after which point it saturates at \( \epsilon_* \sim 75\% \) in all runs except the
Figure 1. Surface density maps at $t = 3t_f$ for the different values of $\Sigma_{\text{cloud}}$ (panels) with the corresponding star formation efficiency ($\epsilon_s$) annotated. Star symbols indicate sink particles, coloured by their mass (see inset colour bar in lower right panel). Vectors (black) indicate the mass-weighted projected velocity field, with arrow length indicating velocity magnitude. The scale for the velocity vectors is annotated in the lower right panel. The surface densities and positions are scaled to $\Sigma_{\text{cloud}}$ and $R_{\text{cloud}}$, respectively. Animations of the time evolution of these maps are available as supplementary online material.

The lowest $\Sigma_{\text{cloud}}$ case, as expected, has the vast majority of its cloud mass ejected ($\epsilon_{\text{ej}} \sim 45\%$). However, it is more interesting to notice that there are marginal, but non-negligible differences in $\epsilon_{\text{ej}}$ between run S3UVIR and the higher $\Sigma_{\text{cloud}}$/No-RT cases for $t > 4t_f$, in spite of their evolution in $\epsilon_s$ being indistinguishable. This is due to the outflows driving mass out of the domain. It is interesting to note that even though the gas morphology and kinematics shows signs of outflowing gas in S4UVIR, the mass removed from the domain is negligible – as evident from Figure 3. However, this is likely because the outflows are initiated only at late times, and thus we have not run the simulations for sufficient time for this gas to escape the domain; visual inspection of the time evolution of the clouds confirms this is the case. These results suggest that for i) $\Sigma_{\text{cloud}} \sim$ few $10^2 \, M_\odot \, \text{pc}^{-2}$, radiation pressure can regulate $\epsilon_s$, and drive a significant fraction of its mass as outflows, ii) for $\Sigma_{\text{cloud}} \lesssim 10^3 \, M_\odot \, \text{pc}^{-2}$, radiation pressure cannot regulate $\epsilon_s$, but once high $\epsilon_s$ is reached, clusters formed in such clouds can drive outflows, and iii) for $\Sigma_{\text{cloud}} \gtrsim 10^5 \, M_\odot \, \text{pc}^{-2}$, lowest surface density case ($\Sigma_{\text{cloud}} = 3.2 \times 10^2 \, M_\odot \, \text{pc}^{-2}$), which saturates at $\epsilon_s \sim 58\%$. The former value is similar to that obtained in a control run without feedback (labelled NoRT in Figure 3). This implies that even though radiation forces in runs S3UVIR and S4UVIR drive outflows, this has no discernible impact on $\epsilon_s$. This is because the outflows begin only after these runs reach their respective final $\epsilon_s$ values. The finding that radiation feedback is unable to regulate $\epsilon_s$ for $\Sigma_{\text{cloud}} \lesssim 10^2 \, M_\odot \, \text{pc}^{-2}$ is consistent with the results of Paper I, who only studied the 3 higher $\Sigma_{\text{cloud}}$ values in our present simulation suite. We note that although Paper I only considered the effects of IR radiation pressure, and did not include the UV radiation pressure, this conclusion remains unchanged.

We also quantify the fraction of gas ejected from the volume, $\epsilon_{\text{ej}}$ (Figure 3; bottom panel), where

$$\epsilon_{\text{ej}} = \frac{M_{\text{ej}}}{M_{\text{cloud}}}$$

such that $M_{\text{ej}}$ is the gas mass ejected from the computational volume.

\[ M^* (M_\odot) \]

\[ \Sigma / \Sigma_{\text{cloud}} \]

\[ 10^1 \]

\[ 10^0 \]

\[ 10^2 \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ 10^4 \]

\[ 10^5 \]

\[ 50 \, \text{km s}^{-1} \]

\[ 10^4 \]

\[ 10^5 \]

\[ \Sigma_{\text{cloud}} = 3.2 \times 10^2 \, M_\odot \, \text{pc}^{-2} \]

\[ \epsilon_s = 58\% \]

\[ \Sigma_{\text{cloud}} = 3.2 \times 10^3 \, M_\odot \, \text{pc}^{-2} \]

\[ \epsilon_s = 3\% \]

\[ \Sigma_{\text{cloud}} = 3.2 \times 10^4 \, M_\odot \, \text{pc}^{-2} \]

\[ \epsilon_s = 58\% \]

\[ \Sigma_{\text{cloud}} = 3.2 \times 10^5 \, M_\odot \, \text{pc}^{-2} \]

\[ \epsilon_s = 68\% \]

\[ \Sigma_{\text{cloud}} = 3.2 \times 10^3 \, M_\odot \, \text{pc}^{-2} \]

\[ \epsilon_s = 68\% \]

\[ \Sigma_{\text{cloud}} = 3.2 \times 10^5 \, M_\odot \, \text{pc}^{-2} \]

\[ \epsilon_s = 68\% \]
radiation pressure can neither regulate $\epsilon_s$ nor otherwise affect the dynamics at any significant level.

To quantify why this is the case, we look at the time-evolution of the Eddington ratio averaged over the full sphere, $\langle f_{\text{Edd}} \rangle_{4\pi}$, where the Eddington ratio $f_{\text{Edd}}$ is given by the ratio of specific radiation ($\dot{p}_{\text{rad}}$) and gravity forces ($\dot{p}_{\text{grav}}$).

$$f_{\text{Edd}} \equiv \frac{\dot{p}_{\text{rad}}}{\dot{p}_{\text{grav}}}.$$  

We use the following procedure to compute $\dot{p}_{\text{rad}}$ and $\dot{p}_{\text{grav}}$. We define a spherical coordinate system centred on the instantaneous centre of mass of the sink particles, and assign every computational cell to one of 128 radial bins relative to this point. We compute the direction of the radial vector $\hat{r}$ relative to the centre of mass, and use it to compute

$$\dot{p}_{\text{rad}} = \frac{(\kappa_{\text{R,UV}} F_{0,\text{UV}} + \kappa_{\text{R,IR}} F_{0,\text{IR}})}{c} \cdot \hat{r},$$

where $F_{0,\text{UV}}$ and $F_{0,\text{IR}}$ are the radiation fluxes in the co-moving frame of the fluid in the UV and IR band, respectively. The corresponding (specific) gravitational force $\dot{p}_{\text{grav}}$ is given by

$$\dot{p}_{\text{grav}} = g_{\text{gas}} + g_s,$$

where $g_{\text{gas}} = -\hat{r} \cdot \nabla \Phi_{\text{gas}}$ and $g_s = -\hat{r} \cdot \nabla \Phi_s$, and $\Phi_{\text{gas}}$ and $\Phi_s$ are the gravitational potentials of the gas and sink particles, respectively. To compute $\langle f_{\text{Edd}} \rangle_{4\pi}$, we simply take the volume average $f_{\text{Edd}}$ over all the cells in each radial bin.

We plot $\langle f_{\text{Edd}} \rangle_{4\pi}$ for the different $\Sigma_{\text{cloud}}$ cases for $t = [2, 3, 5, 7] t_{\text{ff}}$ in Figure 4. We see that the differences and temporal behaviour found in our simulations are consistent with the variations in $\langle f_{\text{Edd}} \rangle_{4\pi}$. The $\Sigma_{\text{cloud}} = 3.2 \times 10^2 \, M_\odot \, pc^{-2}$ case is super-Eddington at all times for radii $\leq R_{\text{cloud}}$. The $3.2 \times 10^3 \, M_\odot \, pc^{-2}$ cloud is sub-Eddington at earlier times ($t/t_{\text{ff}} \leq 2$) and then becomes super-Eddington at $t \geq 3t_{\text{ff}}$. Interestingly, the $\Sigma_{\text{cloud}} = 3.2 \times 10^4 \, M_\odot \, pc^{-2}$ case – at late times ($t \geq 5t_{\text{ff}}$) – shows a super-Eddington profile for $r \leq R_{\text{cloud}}$, but is sub-Eddington at larger radii, more so at later times. This could potentially explain the behaviour of $\epsilon_{\text{ff}}$ for this run – i.e., gas at small radii is expelled in an outflow, but rather than escaping to infinity it decelerates and falls back onto the cloud once it reaches larger radii, where the gas is largely sub-Eddington; indeed, this behaviour

Figure 2. Same as Figure 1, but at time $t = 7t_{\text{ff}}$. 

\[\text{Figure 2. Same as Figure 1, but at time } \times \text{ff}.\]
is visible in the velocity fields in the corresponding panel for this run (lower-left) in Figure 2. Therefore significant mass does not escape the domain in spite of the dynamical signatures of outflows in the gas distributions.

3.2 Outflows driven by radiation pressure

Since we find that gas is driven radially outwards by radiation pressure forces in some of our model clouds, in this section we examine the properties of the outflows in more detail. We begin by calculating the radial velocity of the gas \( \mathbf{v} \cdot \hat{r} \) over the domain, where \( \hat{r} \) is the radial unit vector with respect to the centre of mass of the sink particle distribution. We then perform a (volume-)average of this quantity over all solid angles for spherical shells at different \( \tau \) (similar to \( \langle f_{\text{Edd}} \rangle_{4\pi} \)) to obtain the average radial velocity of gas as a function of radius, i.e., \( \langle \mathbf{v} \cdot \hat{r} \rangle_{4\pi} \). We show this quantity at different times for our fiducial runs in Figure 5.

We see that the radial velocities are increasing with time, and are positive over a reasonable extent of the cloud in all cases except the largest \( \Sigma_{\text{cloud}} \) case, where the gas is inflowing at all radii. In the lowest \( \Sigma_{\text{cloud}} \) case, the gas is outflowing at up to ~ 6x the escape speed, even at early times. The S3UVIR run exceeds escape speeds by a factor of ~ 2–2.5 at later times, while the S4UVIR cloud does so only at late times, and even then not over the entire extent of the cloud, consistent with the behaviour of \( \langle f_{\text{Edd}} \rangle_{4\pi} \) in Figure 4.

We also compute the mass flux \( M_{\text{out}} \) across the cloud boundary (i.e., the Cartesian surfaces at \( R_{\text{cloud}} \)) as a function of time. To compute \( M_{\text{out}} \), we integrate the radial component of the momentum flux over the cartesian surfaces at \( R_{\text{cloud}} \) (denoted by \( \partial S \)), i.e.,

\[
M_{\text{out}} = \int_{\partial S} dA \rho (\mathbf{v} \cdot \hat{n}) ,
\]

where \( \hat{n} \) is the unit vector normal to the Cartesian surface, and \( dA \) the surface area. We show the time evolution of \( M_{\text{out}} \) for the fiducial set of simulations in Figure 6, scaled by \( M_{\text{cloud}} / \eta \). We can see that there is a net outflow of material (\( M_{\text{out}} > 0 \)) for all runs except S5UVIR, with the time at which outflows begin increasing with \( \Sigma_{\text{cloud}} \). To compute a characteristic outflow speed for each case, we define \( v_{\text{out}} \), the momentum-flux weighted radial velocity, which is given by

\[
v_{\text{out}} = \frac{\int_{\partial S} dA \rho (\mathbf{v} \cdot \hat{n}) \mathcal{H} (\mathbf{v} \cdot \hat{n}) (\mathbf{v} \cdot \hat{r})}{\int_{\partial S} dA \rho (\mathbf{v} \cdot \hat{n}) \mathcal{H} (\mathbf{v} \cdot \hat{n})} .
\]

where \( \mathcal{H} \) is the Heaviside step function. We apply the Heaviside filter to ensure that \( v_{\text{out}} \) does not diverge even if there is a mixture of outflowing and inflowing gas at the cloud boundary surface, so that \( M_{\text{out}} \) is nearly zero due to cancellations. However, this also means that \( v_{\text{out}} > 0 \) by construction, even if there is no outflow being driven. For this reason we only compute \( v_{\text{out}} \) for times where \( M_{\text{out}} > 0 \); we show this in the lower panel of Figure 6, scaled by the cloud escape speed \( v_{\text{esc}} \); see Table 1. We also compute the time-averaged values of \( M_{\text{out}} \) and \( v_{\text{out}} \) for times where outflows are driven, which we report in Table 2.

We can see that there is a clear progression of \( v_{\text{out}} \) from larger to smaller values for higher \( \Sigma_{\text{cloud}} \). This essentially occurs because the gravitational potential wells are deeper at higher \( \Sigma_{\text{cloud}} \) and the resulting Eddington ratios are lower (Figure 4).

We also compute the total radial momentum in the ejected outflow, \( p_{\text{out}} \), given by

\[
p_{\text{out}} = \int dt \int_{\partial S} dA \rho (\mathbf{v} \cdot \hat{n}) \mathcal{H} (\mathbf{v} \cdot \hat{n}) (v \cdot \hat{r}) .
\]

We normalise this by the final mass of stars formed, to obtain \( p_{\text{out}} / M_{*} \). This is useful to estimate the possible impact the outflows might have on the larger-scale ISM, and to compare with corresponding estimates made for clouds with lower surface densities in earlier studies (e.g., Kim et al. 2018). We report the values of \( p_{\text{out}} / M_{*} \) in Table 2. We see that \( p_{\text{out}} / M_{*} \) is relatively low, and is significantly lower than the typical estimates for supernova feedback (e.g., Kim & Ostriker 2015; Gentry et al. 2017, 2019), suggesting that the radiation pressure-driven outflows are relatively insignificant on larger scales. We note, however, that our simulations lack the ionising UV radiation, which could possibly increase the estimates of \( p_{\text{out}} / M_{*} \), although it is likely to be at most a factor ~ few.

3.3 UV and IR radiation forces

Our simulations allow us to quantify the relative effects of the radiation forces in the UV and IR band, and thereby their contributions in setting the Eddington ratios in Figure 4. To do so, we calculate the cumulative radiation pressure forces separately in the UV and IR bands for our fiducial runs. The forces are defined in a similar fashion to Equation 20, to produce the cumulative UV radiation force given by

\[
\rho_{\text{UV, cum}} = \int_{0}^{R_{\text{cloud}}} \left( \frac{e_{\text{R, UV}} F_{0, \text{UV}}}{c} \right) 4\pi r^{2} dr ,
\]
and the cumulative IR radiation force
\[ \rho_{\text{IR,cum}} = \int_0^{R_{\text{cloud}}} \left( \frac{\rho_{\text{IR}} F_{\text{IR},}\lambda}{L_x/c} \right) 4\pi r^2 dr, \]  
(26)

In Figure 7, we show the time-averaged values of \( \rho_{\text{UV,cum}} \) and \( \rho_{\text{IR,cum}} \), and their combined force (i.e., \( \rho_{\text{UV,cum}} + \rho_{\text{IR,cum}} \)), normalised by \( L_x/c \), where \( L_x \) is the total (UV) luminosity output from the sink particles at a given time. The quantity \( L_x/c \) denotes the maximum cumulative momentum that is available in the single-scattering limit – i.e., this is the maximum possible value of \( \rho_{\text{UV,cum}} \). When the cloud is in the multiple scattering limit, the cumulative IR radiation force can exceed this value, and the factor by which it does so is referred to as the trapping factor, \( f_{\text{trap}} \). We can see from Figure 7 that the true cumulative UV radiation force is \( \leq 0.1 L_x/c \), for reasons that we explore in Section 3.4. On the other hand, for the IR, \( f_{\text{trap}} \geq 1 \) for \( \Sigma_{\text{cloud}} \geq 10^4 \, M_\odot \, \text{pc}^{-2} \), with \( f_{\text{trap}} \approx 10 \) for the highest \( \Sigma_{\text{cloud}} \) case. We note that these values of \( f_{\text{trap}} \) are lower than those obtained for the same parameters in the IR-only control runs (2.5 and 18, respectively; c.f. Figure 19 in Paper I). This is probably due to Paper I’s idealised approach of injecting IR photons with a Gaussian source term (Equation 15), which can lead to a more systematic force in the radial direction than an asymmetric injection of IR photons via the reprocessing of UV radiation. We can also quantify the overall relative importance of the UV and IR radiation forces from Figure 7. We can see that the lowest (highest) \( \Sigma_{\text{cloud}} \) is clearly dominated by the UV (IR) radiation force. The \( \Sigma_{\text{cloud}} \approx 10^5 \, M_\odot \, \text{pc}^{-2} \) case is also dominated by the IR radiation force, which is \( \approx 10 \) times the UV. On the other hand, for \( \Sigma_{\text{cloud}} \approx 10^5 \, M_\odot \, \text{pc}^{-2} \) the forces in the UV and IR bands are comparable, and hence equally important to the dynamics of the clouds. Therefore, this implies that it is important to consider the contribution of both UV and IR radiation forces for clouds with \( \Sigma_{\text{cloud}} \approx 10^5 \, M_\odot \, \text{pc}^{-2} \); however, for clouds that have higher (lower) surface density, the UV (IR) radiation forces are negligible and can be ignored.

Another approach to quantify the relative importance of the UV and IR radiation pressure is to compare the fiducial runs with control runs that do not include one of the bands (i.e., SnUV and SnIR runs; Table 1). In Figure 8 we compare \( \langle f_{\text{Edd}} \rangle_{4\pi} \) at \( t = 7 \, t_{\text{ff}} \) between these simulations. The crucial role played by the UV radiation pressure is clearly visible here; the SnIR runs are all sub-Eddington at all \( r \). However, \( \langle f_{\text{Edd}} \rangle_{4\pi} \) can be up to factors of a few higher in the UV+IR runs than the UV-only version, especially at smaller \( r \). This is likely because the IR radiation pressure is concentrated at small \( r \), as the temperatures, and hence the opacities, are lower at larger \( r \); visual inspection confirms this is the case. We can also identify the impact the forces have on the dynamics of the clouds by comparing

Figure 4. Angle-averaged, volume-weighted Eddington ratio (based on Eq. 19) compared at different times for different \( \Sigma_{\text{cloud}} \) (panels). The corresponding line for \( \Sigma_{\text{cloud}} = 3.2 \times 10^2 \, M_\odot \, \text{pc}^{-2} \) at \( t = 7 \, t_{\text{ff}} \) is not plotted as there is no gas remaining in the domain.
Figure 5. Volume-weighted radial velocity averaged over radial shells at radius r and times $t = [3, 5, 7] \, t_{\text{ff}}$. The dotted lines indicate zero radial velocities, and the dashed lines indicate the escape speed of the cloud ($v_{\text{esc}}$), with their values annotated.

The IR-only cases have negative $v \cdot \hat{r}$ between the runs at the same time, as shown in Figure 9. The differences in this quantity between the fiducial runs and the UV/IR-only control runs are quite evident in the cases of intermediate $\Sigma_{\text{cloud}}$; the lowest and highest $\Sigma_{\text{cloud}}$ cases are more or less indistinguishable from their UV and IR controls runs, respectively, as expected. In both the intermediate $\Sigma_{\text{cloud}}$ cases, the UV+IR cases have higher (positive) $\langle v_r \rangle_{4\pi}$ than the UV-only case, and a larger fraction of gas that exceeds the escape speed of the cloud\(^9\). That being said, even the UV-only cases have radial velocities that exceed $v_{\text{esc}}$, suggesting that outflows are still driven in these runs, but that they involve a smaller fraction of the cloud than in the UV+IR runs.

This behaviour can also be inferred from the time-averaged properties of the outflows driven in the UV-only control runs – summarised in Table 2. We see that $v_{\text{out}}$ in these runs is more or less comparable to that in the runs with UV+IR for all $\Sigma_{\text{cloud}}$. However, for intermediate $\Sigma_{\text{cloud}}$, $M_{\text{out}}$ is lower in the UV-only runs by a factor $\sim 2$, indicating that the inclusion of the IR radiation pressure significantly enhances the mass in the outflows. Similarly, the outflows carry more momentum ($p_{\text{out}}/M_*$) with the inclusion of the IR component, especially for the S4UVIR run. These findings, combined with the behaviour of $\langle f_{\text{Edd}} \rangle_{4\pi}$ and $\langle v_r \rangle_{4\pi}$ in Figures 8 and 9, suggest that i) the outflows are initiated primarily by the impulse provided by the UV radiation pressure, and ii) the added component of the IR radiation pressure renders a larger fraction of sight-lines around the radiation sources super-Eddington, and thereby entrains more mass into the outflows.

3.4 Low efficiency of radiation pressure forces

In Figure 7, we quantified the total radial momentum per unit time injected by the UV and IR radiation pressures, in units of $L_*/c$ – the momentum flux carried by photons from the sink particles. For an idealised spherical distribution with a source at the centre and enough mass around it to be optically thick in the UV, this ratio for the UV case should be 1 (i.e., the momentum per unit time imparted to the gas $= L_*/c$), and should be $\tau_{\text{IR}}$ for IR radiation, where $\tau_{\text{IR}}$ is the cumulative optical depth in the IR. We find that these idealised estimates are much higher than that obtained in our simulations. In Paper I we explain the origin of this discrepancy for the IR radiation pressure, so we do not repeat that analysis here. However, this still leaves the question of why the cumulative momentum injection rate in the UV is lower in our simulations, as shown in Figure 7.

We find that the reason the momentum delivered to the gas is

\(^9\) The IR-only cases have negative $\langle v_r \rangle_{4\pi}$ at all $\Sigma_{\text{cloud}}$, consistent with their sub-Eddington states.
small is due to the cancellation of forces in the radial direction – with respect to the centre of mass of the sources (sink particles) – which occurs as most of the UV radiation is absorbed close to the sources, over regions whose sizes are smaller than/comparable to the typical separation between sources. We refer to the scales over which the UV radiation is absorbed and over which the sources are distributed as $d_{UV}$ and $d_*$, respectively. We can see in Figure 10 – which is a projection of the UV energy absorption rate at $t = 5t_{ff}$ for our fiducial runs – that $d_{UV} \leq d_*$. For such a situation, the individual (radial) vector forces from each sink, which point radially outwards with respect to the sink, need not necessarily point radially outwards with respect to the centre of mass, leading to a reduction in the radial momentum injection to the cloud. If, on the other hand, $d_{UV} \gg d_*$, the sinks would all lie within their respective UV absorption zones, and would all contribute positively to the radial momentum.

This helps explain why the efficiency of UV momentum injection is low in all our runs, and more so in the highest $\Sigma_{cloud}$ case ($\sim 0.01L_*/c$) – since $d_*$ is very small at these high surface densities (see Figure 10). However, the low efficiency of the $\Sigma_{cloud} = 3.2 \times 10^3 M_\odot$ pc$^{-2}$ case needs further explanation. The cloud is being dispersed by (UV) radiation pressure in this case, and thus $d_{UV}$ should increase as time progresses, rendering the UV momentum injection more efficient. However, we find that this is countered by another effect: as the cloud expands, this opens up channels through which UV photons escape, decreasing the efficiency of momentum injection, eventually driving it to zero as the cloud is entirely dispersed. It is possible that the combination of these two effects leads to the low time-averaged efficiency of $\sim 0.1\%$ we find. To investigate whether this is the case, we show the time evolution of the radial momentum injection rate for this run in Figure 11. Consistent with our hypothesis, we find that the efficiency is low at early times, then goes up as the bulk of the gas is pushed outwards and the gas distribution increasingly satisfies the condition $d_{UV}/d_* \gg 1$. However, for $t > 3t_{ff}$, the efficiency decreases again due to the escape of UV photons through channels opened up by the dispersing cloud – the top-left panel of Figure 10 provides a visual confirmation of this scenario. By comparing with Figure 3 we also see that i) the increase in momentum injection at $t \geq 1.5t_{ff}$ corresponds to when $\epsilon_*$ starts to saturate due to radiation pressure forces and the associated expansion of a shell, and ii) the decrease in momentum injection for $t \geq 3t_{ff}$ corresponds to when $\epsilon_{1/2} > 0$, indicating that gas has started to escape the domain, opening up channels for UV radiation to escape.

The aforementioned scenario shows that it matters where the UV photons are absorbed with respect to the distribution of the radiating source(s). An interesting implication of this is that the UV radiation pressure is likely to be a much more efficient feedback mechanism for a single massive star/binary system than for a larger system such as a molecular cloud/star cluster\textsuperscript{10}. In the former case, there is less potential for cancellation due to a lower number of sources. In addition, for a massive star, the UV absorption front can be moved outwards due to the destruction of dust; indeed, for a single massive star or close binary, the dust destruction radius is much larger than the system scale, while for even the most compact star clusters the opposite is the case. This further reinforces the point made by Krumholz (2018) that calculations of radiation pressure feedback are only reliable if

\textsuperscript{10} Efficient in this context is in terms of the fraction of the total available UV radiation momentum ($L_*/c$) that is effectively imparted to gas in the radially outward direction.

Figure 6. Time evolution of the (normalised) mass outflow rate ($M_{out}$; top), and the momentum-flux weighted outflow velocity ($v_{out}$), normalised by $v_{esc}$ (bottom), for runs with different $\Sigma_{cloud}$. We only show $v_{out}$ for times at which $M_{out} > 0$, indicating a net outflow of gas; the corresponding line for S5UVIR is not present as there is no bulk outflow in this case.

Figure 7. The cumulative momentum rate over all radii scaled by $L_*/c$ that is imparted individually by the UV (Equation 25; squares) and IR (Equation 26; diamonds) radiation pressures, and the combination of the two (circles), in the S5UVIR series.
they resolve the region over which radiation is absorbed, and that naive subgrid models that do not include effects such as cancellation or the trapping of radiation momentum by gravity on small scales may be unreliable.

A final implication is that any other feedback mechanism that moves $d_{UV}$ to larger scales – such as hot stellar wind-driven bubbles or hard ionising radiation that can destroy dust grains and/or provide additional thermal pressure-driven expansion – would also increase the momentum injected by UV photons closer to $L_\odot c$. Therefore, it is possible that the UV momentum injection efficiency is higher if additional feedback mechanisms are active.

4 SUMMARY AND DISCUSSION

We conduct 3D radiation hydrodynamic (RHD) simulations of star cluster formation and evolution in massive, dusty, self-gravitating clouds under the influence of direct UV and dust-reprocessed IR radiation pressure. We use the VETTA RHD module (Menon et al. 2022b) – which employs the variable Eddington tensor (VET) closure – to track the propagation of both UV and IR photon bands, accounting for the coupling between the bands due to the reprocessing of UV photons to the IR by dust. We explore marginally bound clouds with gas surface densities of $\Sigma_{\text{cloud}} \approx 3.2 \times 10^2 M_\odot pc^{-2}$, which ranges from the upper end of the single-scattering limit deep into the multiple-scattering regime (see Table 1). We also explore the relative importance of the UV and IR radiation pressure mechanisms by comparing with control runs where one band or the other is omitted. Combining IR and UV radiation pressure, we draw the following conclusions:

- The star formation efficiency $\epsilon_s$ cannot be regulated by radiation pressure for clouds with $\Sigma_{\text{cloud}} \gtrsim 10^3 M_\odot pc^{-2}$, even with the inclusion of the UV radiation pressure. In the simulations studied here, which do not include other forms of feedback except radiation pressure, and with isolated clouds that do not receive any energy input from a larger galactic environment, $\epsilon_s$ reaches ~ 80% within $t \sim 3 t_{ff}$ regardless of whether we include IR radiation, UV radiation, or both. We refer the reader to Paper I (Section 4.4) for a discussion of how these values of $\epsilon_s$ compare to observed estimates.
- However, clouds with $\Sigma_{\text{cloud}} \lesssim 10^5 M_\odot pc^{-2}$, on attaining high $\epsilon_s$, become super-Eddington and launch radiation-pressure driven radial outflows – unlike the lack of any dynamical impact of feedback in Paper I based on IR only.

Figure 8. Eddington ratio compared at $t = 7 t_{ff}$ for different $\Sigma_{\text{cloud}}$ (panels) separated by the bands evolved in the simulations.
Table 2. Summary of key simulation results.

| Model   | $\epsilon_s$ | $\epsilon_{ej}$ | $M_{out}$ [M$_{\odot}$ yr$^{-1}$] | $M_{out}$/(M$_{\text{cloud}}$/ft) | $v_{out}$/M$_{esc}$ | $p_{out}$/M$_{esc}$ | $p_{\text{cum,UV}}$/(L$_*/c$) | $p_{\text{cum,IR}}$/(L$_*/c$) | $p_{\text{cum,IR}}$/p$_{\text{cum,UV}}$ |
|---------|---------------|-----------------|---------------------------------|---------------------------------|-----------------|----------------|----------------------------|----------------------------|----------------------------|
| S2VIR   | 0.58          | 0.4             | 0.029                           | 0.085                           | 28              | 1.7            | 0.14                      | 0.0067                    | 0.048                      |
| S3VIR   | 0.74          | 0.18            | 0.012                           | 0.0064                          | 25              | 0.88           | 0.09                      | 0.11                      | 1.2                       |
| S4VIR   | 0.75          | 0.14            | 0.093                           | 0.0086                          | 16              | 0.31           | 0.059                     | 1.3                       | 23.0                      |
| S5VIR   | 0.73          | 0.15            | –                               | –                               | –               | –              | –                         | 0.065                     | 0.0                       |
| S2V     | 0.6           | 0.32            | 0.0075                          | 0.004                           | 32              | 2.0            | 0.19                      | 0.0                       | 0.0                       |
| S3V     | 0.75          | 0.16            | 0.0074                          | 0.0045                          | 30              | 1.3            | 0.08                      | 0.0                       | 0.0                       |
| S4V     | 0.75          | 0.15            | 0.048                           | –                               | –               | –              | –                         | 0.065                     | 0.0                       |

Notes: Columns in order indicate - Model: model name, $\epsilon_s$: fraction of mass in stars, $\epsilon_{ej}$: fraction of mass ejected from the domain, $M_{out}$: mass outflow rate, $M_{out}$/(M$_{\text{cloud}}$/ft): mass outflow rate scaled by the cloud mass and free fall time, $v_{out}$: average momentum-flux weighted outflow velocity, $v_{out}$/M$_{esc}$: outflow velocity scaled by the cloud escape speed $v_{esc}$, $p_{out}$/M$_{esc}$: momentum per unit stellar mass carried by the outflowing gas, $p_{\text{cum,UV}}$/(L$_*/c$): cumulative momentum imparted by the UV radiation pressure in units of L$*/c$, $p_{\text{cum,IR}}$/(L$_*/c$): cumulative momentum imparted by the IR radiation pressure in units of L$*/c$, $p_{\text{cum,IR}}$/p$_{\text{cum,UV}}$: ratio of total momentum imparted by IR and UV radiation pressures.

- The outflows can reach significant radial velocities with high fractions of the escape speed of the clouds, $v_{out}$ ~ 0.5–2 $v_{esc}$ (see Table 2) – corresponding to ~ 15–30 km s$^{-1}$ – with the outflow velocity decreasing with $\Sigma_{\text{cloud}}$. However, the momentum carried in the ejected outflows ($p_{out}$/M$_*$ ≤ 10 km s$^{-1}$) is too small to directly affect ISM dynamics at kiloparsec-scales and beyond.

- The cumulative momentum imparted by the UV and IR radiation pressure is comparable for $\Sigma_{\text{cloud}} \sim 10^3$ M$_{\odot}$ pc$^{-2}$, and is dominated by the IR (UV) component in clouds with higher (lower) surface densities.

- The characteristic outflow velocity for clouds in the multiple-scattering limit ($\Sigma_{\text{cloud}} \gtrsim 10^3$ M$_{\odot}$ pc$^{-2}$) does not depend on whether
we include only UV radiation pressure or both UV and IR (Table 1), but the mass outflow rates and momentum fluxes do: omitting the IR lowers both by factors $\sim 2$. This suggests that the impulse of the UV radiation force provides the launching mechanism of the outflow, while the effect of IR radiation pressure is to render a larger fraction of the gas unbound, thereby allowing the UV pressure to entrain significantly more mass.

- We find that the cumulative momentum imparted by UV photons can be significantly lower than $L_*/c$, more so at higher $\Sigma_{\text{cloud}}$. This occurs due to radiation forces cancelling each other out when radiation is absorbed on scales smaller than the typical spatial separation between radiation sources (see Section 3.4).

Our finding that radiation pressure can drive outflows even in clouds with steep gravitational potential wells ($\sim 10^4 \, M_\odot \, \text{pc}^{-2}$) is interesting and may be significant in the context of the formation and evolution of super-star clusters (SSCs). For instance, Levy et al. (2021) (L21 hereafter) analyse high-resolution ($\sim 0.5 \, \text{pc}$) ALMA observations of SSCs in the starburst galaxy NGC 253, and find that a subset of their sample shows signs of (dense-gas) outflows. We can crudely compare the reported properties of the clouds and outflows in their observations (Table 2 in L21) with our simulations (Table 2). The clusters with outflows reported in L21 have $v_{\text{out}} \sim 6$–20 km s$^{-1}$, and $p_{\text{out}}/M_* \sim 1$–5 km s$^{-1}$ – in reasonable agreement with the values we find. This suggests that radiation pressure is a strong candidate for driving these outflows. Similarly, our results seem to suggest that a potential outflow of molecular gas observed in NGC 2366, coincident with the Mrk 71-A SSC ($v_{\text{out}} \sim 11$ km s$^{-1}$; Oey et al. 2017) is likely driven by radiation pressure.

A minor caveat is that the star clusters with outflows in L21 have estimated surface densities of $\gtrsim 10^5 \, M_\odot \, \text{pc}^{-2}$, slightly beyond the range of $\Sigma_{\text{cloud}}$ where we find outflows are driven. That being said, there are significant uncertainties in the estimated stellar masses and radii of the clusters that go into calculating $\Sigma$ (Leroy et al. 2018). Moreover, the $\Sigma$ estimated in L21 is for the observed snapshot wherein the cluster has already formed, whereas $\Sigma_{\text{cloud}}$ in our

Figure 10. Projected maps of the local UV energy absorption rate at $t = 3t_{\text{ff}}$ for the different values of $\Sigma_{\text{cloud}}$ (panels). The absorption rate is normalised by the maximum value of the quantity in each panel. The star symbols and axes normalisation are similar to those of Figure 1. We see that the UV radiation is absorbed close to the sink particles for higher $\Sigma_{\text{cloud}}$, and the scale over which absorption occurs is small compared to the scale over which the sink particles are distributed. This explains the relatively low efficiency of radial momentum injection by radiation pressure due to cancellation of radiation forces.
simulations is the initial condition; $\Sigma$ would significantly increase as the cloud collapses under the action of gravity and becomes more compact. We also have to point out larger fractions of our clouds could be ejected at a given $\Sigma_{\text{cloud}}$ if i) the clouds were unbound to begin with (i.e., having a larger virial parameter), as suggested by some observations (Evans et al. 2021), and might be expected to occur in the extreme environments where these clouds form, such as mergers, or ii) through the inclusion of magnetic fields (Federrath & Klessen 2012) and/or additional early feedback mechanisms (e.g., stellar winds, photoionisation) in our simulations, and/or iii) a higher dust-to-gas ratio or a more top-heavy IMF, as have been found in some young super-star clusters (Turner et al. 2015). Therefore, we caution against a direct one-to-one comparison of our model clouds with observed counterparts; rather, we present our findings as evidence that radiation pressure has the momentum budget to drive such outflows. Follow-up observations to better constrain the properties of SSCs and/or extending the sample size would enable testing the viability of these ideas.

While we argue that radiation pressure can indeed launch outflows in star clusters, the same cannot be said for outflows at galactic scales. This is because the galactic discs have significantly larger mass to light ratios than individual young clusters – they are in the “old stars” limit as defined by Dekel & Krumholz (2013) – and thus the gas within them is sub-Eddington to both single-scattering and multiple-scattering radiation pressure (Andrews & Thompson 2011; Crocker et al. 2018a). However, outflows launched by star clusters at GMC scales may continue to be accelerated by UV radiation pressure on dust for longer periods, reaching asymptotic velocities of $v_{\infty} \sim v_{\text{esc}} \left( L_{\star} \kappa_{\text{UV}} / 4\pi G M_{\star} c \right)^{1/2}$, where $L_{\star}$ and $M_{\star}$ are the mass and luminosity of the driving cluster, and $\kappa_{\text{UV}}$ the UV opacity of dust grains, before the wind expands so much that it becomes optically thin and ceases absorbing momentum from the radiation field (Thompson et al. 2015; Raskutti et al. 2017; Krumholz et al. 2017). Substituting values adopted in this study for these quantities produces $v_{\infty} \sim v_{\text{esc}}$, which can be up to 500 km/s for the most compact clusters ($\Sigma_{\text{cloud}} \gtrsim 10^{4} M_{\odot} \text{ pc}^{-2}$). This calculation seems to suggest that some gas may be launched to high galactic latitudes by compact star clusters, and potentially even escape the galaxy; that being said, this estimate is highly idealised, and factors such as the ageing of stellar populations, evolution of the mass in the driven shell, and the nature of extended distributions of star formation in the galaxy would significantly affect our estimate. It is also possible that, if there is significant ionising photon escape from the cluster, the asymptotic velocity could be up to several thousand km/s due to the much larger opacity of neutral hydrogen atoms to ionising and Lyman $\alpha$ photons (Komarova et al. 2021). There is scope to explore the longer term evolution of these outflows and their potential observable features in future work.

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**Software**: PETSc (Balay et al. 1997, 2021), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), Matplotlib (Hunter 2007), yt (Turk et al. 2010). This research has made use of NASA’s Astrophysics Data System (ADS) Bibliographic Services.

**DATA AVAILABILITY**

Outputs of our simulations would be shared on reasonable request to the corresponding author.

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11 However, local patches within galaxies can be super-Eddington in the single-scattering limit (Thompson & Krumholz 2016; Blackstone & Thompson 2023).
APPENDIX A: TEST OF THE UV RADIATION PRESSURE WITH VETTAM

In Paper I, we compared the outcomes of turbulent star-forming clouds regulated by reprocessed IR radiation pressure obtained with the VETTAM RHD algorithm (Menon et al. 2022b), which uses the VET-closure with that obtained in Skinner & Ostriker (2015), which used an $M_1$ closure (Skinner & Ostriker 2013). We found that the resulting values of the integrated star formation efficiency ($\epsilon_*$) were indistinguishable between the two. However, the reprocessed radiation flux is distributed in a more smooth and isotropic fashion than the direct UV radiation from the stars/clusters, and it is possible that the latter may highlight the limitations of the $M_1$ closure. Indeed, Kim et al. (2017) repeated the fiducial simulation outlined in Raskutti et al. (2016) with their Adaptive Ray-Tracing (ART) algorithm, and compared the results to those obtained with the $M_1$ closure used in the original study. They found that the final value of $\epsilon_*$ is lower ($\sim 0.25$) with the more accurate ART method than in the $M_1$ case ($\sim 0.42$). They deduced from the radiation field distributions that the $M_1$ closure underestimates the radiation forces in the vicinity of radiation sources (sink particles), thereby leading to a higher $\epsilon_*$.

Given this finding, it is interesting to test how our VET-based method performs for this problem; although the VET-closure should be of comparable accuracy to an ART method overall, ART is likely more accurate for the regions in the immediate vicinity of the radiation sources since the moment-based VET method requires some form of ad-hoc injection of photons that is smoothed over some length scale (see Section 2), and our calculation of the Eddington tensor uses a fixed angular resolution that is in general lower than the angular resolution of an ART method. To test these effects, we repeat the fiducial simulation in Raskutti et al. (2016) with VETTAM. The model cloud has a value of $M_{\text{cloud}} = 5 \times 10^4 M_\odot$, $R_{\text{cloud}} = 15$ pc, $\alpha_{\text{v}} = 2$, and $\sigma_v = 4.16$ km s$^{-1}$. The numerical setup is identical to the runs presented in the main part of the paper. The only modification is that we use a light-to-mass ratio of $\psi = 2000$ erg s$^{-1}$ to match the value used in Raskutti et al. (2016). We show the resulting time evolution of $\epsilon_*$ for different resolutions. We can see that the obtained values of $\epsilon_*$ are reasonably consistent with the ART value, taking into account that $\sim 10\%$ differences in $\epsilon_*$ can be introduced by different random seeds for driving the initial turbulent motions.

APPENDIX B: CONVERGENCE TEST

We test for numerical convergence of our results by comparing runs with different grid resolutions. We repeat our fiducial simulation, S3UVIR, with uniform-grid resolutions of $64^3$ and $128^3$ to compare with our choice of $256^3$. We found that the obtained values of $\epsilon_*$ and $\epsilon_{\text{ej}}$ were identical to within a few percent, similar to the convergence test presented in Paper I. Instead, we found it more informative to compare the properties of the radiation-driven outflows. In Figure B1, we compare the obtained outflow rates and velocities obtained at different resolutions. We can see that the obtained $M_{\text{out}}$ and $v_{\text{out}}$ are reasonably converged for resolutions of $N > 128^3$, with their average values $\leq 10\%$ of each other in the $N = 128^3$ and $N = 256^3$ runs.

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Figure B1. Same as Figure 6 for the S3UVIR run, compared for simulations with numerical resolutions of $N = 64^3$ (dotted), $N = 128^3$ (dashed), and our fiducial choice of $N = 256^3$ (solid).