The role of non-ionizing radiation pressure in star formation: the stability of cores and filaments

Young Min Seo* and Andrew N. Youdin

Department of Astronomy & Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA

ABSTRACT

Stars form when filaments and dense cores in molecular clouds fragment and collapse due to self-gravity. In the most basic analyses of gravitational stability, the competition between self-gravity and thermal pressure sets the critical (i.e. maximum stable) mass of spheres and the critical line density of cylinders. Previous work has considered additional support from magnetic fields and turbulence. Here, we consider the effects of non-ionizing radiation, specifically the inward radiation pressure force that acts on dense structures embedded in an isotropic radiation field. Using hydrostatic, isothermal models, we find that irradiation lowers the critical mass and line density for gravitational collapse, and can thus act as a trigger for star formation. For structures with moderate central densities, ~10^3 cm^{-3}, the interstellar radiation field in the Solar vicinity has an order unity effect on stability thresholds. For more evolved objects with higher central densities, a significant lowering of stability thresholds requires stronger irradiation, as can be found closer to the Galactic centre or near stellar associations. Even when strong sources of ionizing radiation are absent or extincted, our study shows that interstellar irradiation can significantly influence the star formation process.

Key words: stars: formation – ISM: clouds – ISM: kinematics and dynamics.

1 INTRODUCTION

Star formation is a process by which interstellar gas becomes denser via a hierarchy of structures, with gravitational collapse playing a key role. Dense filaments are ubiquitous in molecular clouds, with 75 per cent of denser starless cores residing in filaments (André et al. 2010). The formation of cores within filaments is explained by gravitational instability (Inutsuka & Miyama 1992). The formation of stars within cores is attributed to another gravitational collapse (Shu, Adams & Lizano 1987).

A basic understanding of gravitational collapse comes from the study of isothermal and pressure-confined gas in hydrostatic equilibrium. The classic solutions are the Bonnor–Ebert (BE) sphere (Ebert 1955, 1957; Bonnor 1956) and the isothermal Ostriker (1964) cylinder. These studies show that gravitational collapse occurs above the critical mass of the BE sphere and the critical line density (mass per length) of isothermal cylinders. The critical BE mass also applies to hydrostatic clouds of any geometry, provided that the volume is finite (Lombardi & Bertin 2001). Observed density profiles of filaments and cores are often well matched by these simple models (e.g. Bacmann et al. 2000; Alves, Lada & Lada 2001; Kandori et al. 2005; Harcar & Tafalla 2011).

While of fundamental importance, these classic solutions neglect many potentially significant effects. Magnetic fields, turbulence and detailed radiative transfer can alter the structure and stability of cores and filaments (McKee & Ostriker 2007). This work focuses on a particular aspect of radiative transfer, the radiation pressure exerted on cores and filaments by ambient non-ionizing radiation. Ionizing radiation is known to have important effects on star formation in H II regions, i.e. near high-mass stars. Our focus on non-ionizing radiation applies not only to low-mass star-forming regions, but also to regions of high column density into which non-ionizing radiation penetrates more deeply.

Non-ionizing radiation (from mid-UV to mid-IR) exerts radiation pressure on dust grains, which are frictionally coupled to the gas (Draine 2011). The radiation pressure force is weak in the diffuse interstellar medium because the interstellar radiation field (ISRF) is almost isotropic, with ~10 per cent anisotropy, (Weingartner & Draine 2001). However, near and inside a dense structure, radiation becomes anisotropic due to shadowing by the structure itself. With this introduced anisotropy, radiation pressure becomes comparable to thermal gas pressure in the interstellar medium.

In this paper, we study how the radiation pressure force alters the structure and gravitational stability of filaments and cores. Section 2 describes our model for hydrostatic irradiated structures. Section 3 presents our self-similar solutions in dimensionless coordinates. In Section 4, we apply our results to the physical conditions of star-forming regions. In Section 5, we discuss limitations and future extensions of our model. We summarize our results in Section 6.
2 MODEL FOR IRRADIATED CYLINDERS AND SPHERES

2.1 Hydrostatic structure with radiation pressure

We consider hydrostatic configurations of dense cores and filaments exposed to non-ionizing photons that exert radiation pressure. Our idealized model assumes spherical symmetry for dense cores and cylindrical symmetry for filaments. Radiation pressure acts on dust grains, which are uniformly mixed and perfectly coupled to the gas. Possible sedimentation of dust grains is addressed in Section 5.

Our models satisfy hydrostatic equilibrium and the Poisson equation:

\[ \nabla p_g = -\rho \nabla \psi + n_d f_{\text{rad}} \quad (1) \]

\[ \nabla^2 \psi = 4\pi G \rho, \quad (2) \]

where \( p_g \) is the gas pressure, \( \psi \) is the gravitational potential, \( f_{\text{rad}} \) is the force exerted to a dust grain due to radiation pressure, \( n_d \) is the number density of dust grains per unit volume and \( \rho = \rho_g + \rho_d \) is the total density of dust and gas, respectively.

The radiation pressure force on a dust grain is

\[ f_{\text{rad}} = \pi a^2 \langle Q_{\text{pr}} \rangle \frac{F_{\text{rad}}}{c}, \quad (3) \]

where \( a \) is the effective spherical radius of dust grains, \( F_{\text{rad}} \) is the energy flux of radiation field, \( c \) is the speed of light and \( \langle Q_{\text{pr}} \rangle \) is radiation pressure efficiency, described in detail in Section 4.1. The mass of a dust grain is

\[ m_d = \frac{\rho_d}{n_d} = \frac{4\pi}{3} \rho_m a^3 \quad (4) \]

with \( \rho_m \) the internal, material density of dust grains.

The radiative flux is directed inwards, \( F_{\text{rad}} = F \hat{r} \) with \( F < 0 \) and \( \hat{r} \) the unit vector along the spherical or cylindrical radial coordinate, \( r \). We consider the extinction of radiation (but ignore scattering) by taking a two-ray approximation (see Fig. 1). One ray, \( F^- \), represents the flux entering the sphere/cylinder from the near surface, while \( F^+ \) represents the oppositely directed flux from the far surface, which has passed through the centre. The total flux \( F = \langle F^- \rangle + \langle F^+ \rangle \) with

\[ F^- = F_0 \exp[-\tau(r)] \quad (5a) \]

\[ F^+ = F_0 \exp[-\tau_{\text{tot}} + \tau(r)]. \quad (5b) \]

The optical depth to the near surface, at \( r = r_0 \), is

\[ \tau(r) = \pi \int_{r_0}^{r} a^2 \langle Q_{\text{pr}} \rangle n_d dr'. \quad (6) \]

\( Q_{\text{pr}} \) is the spectrum-averaged extinction coefficient. The total extinction of a sphere/cylinder is \( \tau_{\text{tot}} = \tau(r_0) \). The normalization \( F_0 \) gives the one-sided surface flux, i.e., \( F(r_0) = -F_0 \) for an opaque object with \( \tau_{\text{tot}} \gg 1 \). The validity of the two-ray approximation is addressed in Section 5.

We adopt an isothermal equation of state for the gas:

\[ P_g = c_s^2 \rho_g, \quad (7) \]

where \( c_s \) is the sound speed of gas, and \( \rho_g \) is the gas density, consistent with the standard BE problem and in at least rough agreement with observed cores and filaments (Evans et al. 2001; Stamatellos et al. 2007; Seo et al. 2015).

Figure 1. Schematic of our two-ray model for the flux of non-ionizing radiation inside a dense core or filament. The net flux at any internal radius \( r < r_0 \) arises from two competing rays: the inward directed flux, \( F^- \), and the outward directed flux, \( F^+ \), that has passed through the centre of the object. An optically thin object in an isotropic radiation field will experience a little net flux as the two contributions nearly cancel.

To derive our version of the Lane–Emden equation, we take the divergence of \( 1/\rho \) times the equation (1), which combined with equation (2) gives

\[ c_s^2 \nabla \cdot \left( \frac{\rho}{\rho + Z} \nabla \psi \right) = -4\pi G \rho + \nabla \cdot \left( \frac{Z + 1}{1 + Z} m_d \right), \quad (8) \]

where the dust-to-gas ratio, \( Z = \rho_d/\rho_g \). Solution of equation (8) also requires equations (3), (5) and (6) to specify the radiation force. To simplify the solution space, we also hold spatially constant both \( Z \) and the dust opacities

\[ \kappa_i = \frac{Z}{1 + 4 \rho_0 a^2} \quad (9) \]

where the index \( i = \text{\textquoteleft ext} \) and \( \text{\textquoteleft pr} \) labels the radiation pressure and extinction cases. In practice, we obtain solutions using the dimensionless equations described below.

2.2 Dimensionless equations

Our dimensionless equations use the central density \( \rho_c \), the dust-weighted sound speed \( c_s' = c_s/\sqrt{1+Z} \), and the characteristic scale height

\[ \alpha \equiv \frac{c_s'}{\sqrt{4\pi G \rho_c}} \quad (10) \]

as scale factors. The dimensionless variables

\[ \xi \equiv \frac{r}{\alpha} \quad (11) \]

\[ s \equiv \frac{\rho}{\rho_c} \quad (12) \]

describe radial distance and density, while \( \tau \) is already dimensionless.

The inclusion of radiative effects adds two new dimensionless parameters. The dimensionless extinction,

\[ \zeta \equiv \kappa_{\text{ext}} \alpha \rho_c \quad (13) \]

MNRAS 461, 1088–1099 (2016)
Figure 2. Left: dimensionless profiles of density, $s$, versus radius, $\xi$, for spheres subject to different levels of (non-ionizing) irradiation, $\Upsilon$, as labelled for the coloured curves. Right: dimensionless mass, $m$, as a function of density contrast, where maximum values correspond to marginal gravitational stability, as described in the text. The dimensionless dust opacity is fixed to $\zeta = 2.6$ in both plots.

Section 2.2. In these sample curves, a large value of optical depth, $\tau_{\text{tot}}$, is assumed so that the density at the outer radius is small, i.e. $s(0) = s(\xi_0) < 10^{-3}$, which corresponds to a large density contrast $\rho_c / \rho_0 = 1 / s_0$. The $\Upsilon = 0$ curve corresponds to the standard BE sphere. As radiation pressure increases (to larger $\Upsilon$), the outer density profile steepens and spheres become radially truncated. Physically, the outward pressure gradient force must increase to balance the inward radiation pressure.

Gravitational stability depends on the curve of dimensionless mass, $m$, versus density contrast. In terms of the dimensional mass $M$ and surface pressure $P_0$,

$$m \equiv \frac{P_0^{1/2} G^{3/2} M}{c_s^3} = \sqrt{\frac{s_0}{4\pi}} \int_0^{\xi_0} s^{3/2} d\xi.$$ (18)

From the right-hand side above, we note that as $s_0$ decreases (and thus the density contrast increases), the prefactor decreases as $\Upsilon$, while the integral increases, due to the larger radius, $\xi_0$. This mathematical competition affects gravitational stability.

Pressure bound spheres are gravitationally unstable if (Bardeen 1965; Stahler 1983):

$$\frac{\partial m}{\partial (\rho_c / \rho_0)} < 0.$$ (19)

This instability criterion is equivalent to the more intuitive Boyle’s law criterion, $\partial P_0 / \partial V_0 > 0$, that gravitating spheres are unstable if an enhanced surface pressure induces expansion to a larger volume, $V_0$ (Bonnor 1956; Lombardi & Bertin 2001). In Appendix A, we verify that this established correspondence also applies in the presence of other forces, such as radiation pressure.

The right-hand panel of Fig. 2 shows $m$ versus density contrast for different values of radiation pressure, $\Upsilon$. At low $m$, solutions are gravitationally stable since $m(\rho_c / \rho_0)$ has a positive slope. The local maximum where $\partial m / \partial (\rho_c / \rho_0) = 0$ defines marginal stability at the critical mass, $m_{\text{crit}}$. For $\Upsilon = 0$, we reproduce the well-known BE mass, $m_{\text{crit}} = 1.18$, and the maximum density contrast of 14.1. As radiation pressure increases (larger $\Upsilon$), both $m_{\text{crit}}$ and the critical density contrast decrease. (But see below for a case where irradiation causes the critical density contrast to increase).

The properties of marginally unstable irradiated spheres are further explored in Fig. 3, which also examines the effect of extinction, via $\zeta$. All the panels in this figure correspond to the critical state with
Role of non-ionizing radiation

1091

Figure 3. Critical values of (from top to bottom) dimensionless mass $m_{\text{crit}}$, size $\xi_{\text{max}}$, density contrast $\rho_c/\rho_0$, and total optical depth $\tau_{\text{tot}}$ for marginally stable irradiated spheres as a function of the dimensionless radiation pressure $\Upsilon$. Different coloured curves correspond to different dimensionless opacities, $\zeta$.

$m = m_{\text{crit}}$, whose values are shown in the top panel. Both this critical mass and the corresponding radius (shown in the second panel) become smaller as either $\Upsilon$ or $\zeta$ increases. Either stronger irradiation or a greater opacity increases the surface radiation pressure force, which scales as $\Upsilon \zeta$ (see equation 16).

The density contrast of critical spheres displays interesting behaviour, shown in the third panel of Fig. 3. For small extinctions, $\zeta \lesssim 1.3$, the density contrast decreases gradually with increasing irradiation, as might be expected for smaller, lower mass spheres. For larger extinctions, however, the density contrast develops a spike near $\Upsilon = 1$. We note that our normalization of the radiation pressure (to the central pressure) is clearly appropriate since interesting behaviour occurs for $\Upsilon \zeta$ near unity.

The origin of the spike in density contrast is explained by the total optical depth of the critical spheres, shown in bottom panel of Fig. 3. The spike in the density contrast corresponds to the transition from high to low total optical depth. The plot shows that only weakly irradiated clouds ($\Upsilon < 1$) can have a high total optical depth and remain stable. In this weakly irradiated regime, the optical depth scales simply with the opacity, via $\zeta$, as radiative effects are not yet significantly affecting cloud structure or stability.

For stronger irradiation, as $\Upsilon$ approaches unity, the maximum optical depth of cores decreases, consistent with their smaller masses and sizes. The spike in density contrast occurs because strong radiation pressure forces, which steepen the density profile, are being felt throughout more of the sphere. For even stronger irradiation, with $\Upsilon$ exceeding unity, the core becomes so transparent that the radiative effects weaken, due to the flux cancellation depicted in Fig. 1. In this highly irradiated regime, the critical density contrast decreases again and the behaviour of critical spheres is surprisingly simple: the total optical depth is order unity value for all extinction values.

In summary, as irradiation increases, the marginally gravitationally stable state gradually transitions from the BE sphere to the sphere with optical depth near unity.

3.2 Irradiated cylinders

Hydrostatic density profiles of irradiated cylinders are shown in Fig. 4. Similar to the spherical case, irradiation steepens the density profile of cylinders at their outer edges. Non-irradiated isothermal cylinder already have very steep outer density profiles, with $s \propto \xi^{-4} (\rho \propto r^{-4})$. In the irradiated cases, even less mass resides at large radii.

An isothermal cylinder does not experience a Bonnor-type instability because $\partial P_0 / \partial V_0$ is always negative (Lombardi & Bertin 2001). Instead, the cylinder becomes unstable only when its line density exceeds the critical line density, which is the line density of a hydrostatic cylinder with infinite outer radius. The critical line density in a dimensionless form is given as

$$\lambda_{\text{crit}} \equiv \frac{G \Lambda_{\text{crit}}}{c_s^2} = \frac{1}{2} \int_0^\infty \xi \lambda \, d\xi,$$

where $\Lambda_{\text{crit}}$ is the dimensionless critical line density of a hydrostatic cylinder. With formally infinite outer radius, the critical cylinder does not have a corresponding radius or density contrast. In reality, of course cylinders are not infinite in radius, and they do have a finite density contrast set by the ambient medium. However, the steepness
4.1 Physical parameters

Our solutions have a constant central number density, \( n_c \), of \( 10^3 \) or \( 10^4 \) cm\(^{-3} \). These values characterize quasi-spherical clumps and young cores, respectively (Bergin & Tafalla 2007). Elongated filaments also span this range of central densities (Arzoumanian et al. 2011).

The effective sound speed
\[
c_s = \sqrt{0.188^2 \left( \frac{T_k}{10 \text{ K}} \right) + \sigma_{\text{st}}^2 \text{ km s}^{-1}} = 0.188 \sqrt{\frac{T_{\text{eff}}}{10 \text{ K}}} \text{ km s}^{-1},
\]
assumes a mean molecular weight of 2.33 proton masses. A kinetic temperature of \( T_k \sim 10 \text{ K} \) is a typical value for dense molecular gas (e.g. Leung 1975; Hotzel, Harju & Juvela 2002; Tafalla et al. 2004). The non-thermal component of the velocity dispersion, \( \sigma_{\text{st}} \), provides at most an order unity correction (e.g. Goodman et al. 1998; Pineda et al. 2010; Hacar et al. 2013; Seo et al. 2015). Our numerical study considers a range of effective temperatures, \( T_{\text{eff}} = 7.5 - 25 \text{ K} \). The corresponding scale height is
\[
\alpha = 0.034 \text{ pc} \left( \frac{c_s}{0.188 \text{ km s}^{-1}} \right) \left( \frac{10^4 \text{ cm}^{-3}}{n_c} \right) \left( \frac{10^2 \text{ cm}^{-2} \text{ s}^{-1}}{\rho_c} \right)^{\frac{1}{2}}.
\]

We fix the dust-to-gas ratio to be \( Z = 0.01 \), a typical interstellar medium value (Draine et al. 2007). For grain sizes, we adopt \( a = 0.05, 0.075, \) and \( 0.1 \mu m \), which are characteristic sizes in molecular regions (Köhler, Ysard & Jones 2015). Though not considered here, our analysis could be extended to accommodate particle size distributions.

We use three models for the chemical composition of dust grains: (1) astro-silicate grains (Weingartner & Draine 2001), (2) carbonaceous grains (Draine 2003), and (3) grains with an ice mantle covering a silicate-carbonaceous core. For the ice mantle grains, we assume a 1:1:1 ratio of astro-silicate, carbonaceous material, and water ice by volume, in agreement with Li & Greenberg (1997).

The material density of dust is assumed to be \( 1 \text{ g cm}^{-3} \) (roughly 50 per cent porosity) for ice grains and ice mantles, \( 1 \text{ g cm}^{-3} \) for carbonaceous (about 40 per cent porosity), and \( 2 \text{ g cm}^{-3} \) (about 40 per cent porosity) for astro-silicates.

For the radiation field, we use the spectrum of the ISRF in the vicinity (Mezger, Mathis & Panagia 1982; Mathis, Mezger & Panagia 1983). Adopted values of the flux, \( F_0 \), range from \( 5 \times 10^{-4} - 0.4 \text{ erg cm}^{-2} \text{ s}^{-1} \). In the Solar vicinity (Galactocentric distance \( D_\odot \sim 8 \text{ kpc} \)), the mean intensity of the non-ionizing ISRF may range from 0.015 to 0.15 erg cm\(^{-2} \) s\(^{-1} \) (Keene 1981; Mezger 1990; Launhardt et al. 2013). These intensities are equivalent to a directed flux of \( F_0 = 0.0025 - 0.025 \text{ erg cm}^{-2} \text{ s}^{-1} \). We calculate the radiative efficiency parameters \( \langle Q_{\text{rad}} \rangle \) and \( \langle Q_{\text{ext}} \rangle \) with the Mie theory code, miex (Wolf & Voshchinnikov 2004) for the grain and radiation properties described above. Fig. 6 shows results of the Mie calculations, both for the adopted ISRF and (for comparison) for main sequence stellar spectra of various effective temperatures (from Pickles 1998).

With the above physical parameters, our dimensionless parameters scale as
\[
\Upsilon = 0.49 \left( \frac{\langle Q_{\text{rad}} \rangle}{\langle Q_{\text{ext}} \rangle} \right) \left( \frac{F_0}{0.02 \text{ erg cm}^{-2} \text{ s}^{-1}} \right) \times \left( \frac{10^4 \text{ cm}^{-3}}{n_c} \right)^{\frac{1}{2}} \left( \frac{0.188 \text{ km s}^{-1}}{c_s} \right)
= 0.01 \left( \frac{Z_\odot}{0.01} \right) \left( \frac{\langle Q_{\text{ext}} \rangle}{1} \right) \left( \frac{n_c}{10^3 \text{ cm}^{-3}} \right)^{\frac{1}{2}} \left( \frac{c_s}{0.188 \text{ km s}^{-1}} \right)
\times \left( \frac{0.1 \mu m}{a} \right) \left( \frac{1 \text{ g cm}^{-3}}{\rho_c} \right),
\]
for the radiation pressure strength and extinction, respectively. The fact that these parameters are order unity suggests (following the
4.2 Gravitational instability criteria with irradiation

4.2.1 Molecular clumps and cores

Fig. 7 shows the critical mass and size of irradiated molecular clumps \((n_c = 10^3 \text{ cm}^{-3})\) and young cores \((n_c = 10^4 \text{ cm}^{-3})\), modelled as 10 K spheres. In the left-hand panels, we use ice-mantle dust grains with three different dust sizes. With weak irradiation, lower density clumps have a higher critical mass and larger critical radius. This behaviour agrees with the standard density scaling of isothermal BE spheres, 

\[
M_{\text{crit}} \propto R_{\text{crit}} \propto 1/\sqrt{n_c}.
\]

As with the self-similar solutions, increased external irradiation decreases critical masses and radii. A given level of irradiation more strongly affects lower density clumps, because radiation pressure is larger relative to the central pressure. Indeed, the irradiation parameter, \(\Upsilon \propto F_0/n_c\) at constant temperature, quantifies this pressure ratio. Thus, while the critical state of clumps is significantly downsized by the radiation fields characteristic of the Solar neighbourhood (the grey bands in Fig. 7), denser cores are significantly affected only when the radiation field approaches levels seen in Galactic centre.

The left-hand panels of Fig. 7 also show that the choices of grain size only modestly affect the critical state of spheres. This result is consistent with the fact (seen in Fig. 6) that efficiency parameters, \((Q)\), increase with the size of small grains so that the relevant combination \((Q)/a\) varies weakly with size in this regime. In other words, optical properties are more sensitive to the grain mass than the grain surface area in the long wavelength regime.

The effects of grain composition are shown in the right-hand panels of Fig. 7. For silicate grains, the effects of irradiation are weaker – as measured by the reduction in critical mass and radius at a given flux – than for carbonaceous or ice-mantle grains. This effect is explained by the lower radiative efficiencies of small silicate grains, as shown in Fig. 6. In a dense molecular region, temperatures are low enough that we do not expect bare silicates. Either the ice-mantle case or carbonaceous cases should be more realistic, depending on the fractional abundance of carbon species (Greenberg & Li 1999).

Table 1 presents critical masses and radii of irradiated spheres for a range of effective temperatures. Critical masses and radii are larger at higher temperatures. Also, at higher temperatures, and thus higher central pressures, a correspondingly stronger external radiation pressure is needed to lower the critical masses and radii.

4.2.2 Molecular filaments

The critical line density of irradiated filaments at 10 K is shown in Fig. 8. In the low-irradiation limit, the critical line density, \(\Lambda_{\text{crit}} = 2c_s^2/G\), is independent of central density, unlike the \(M_{\text{crit}}\) of spheres. Analogously to the spherical case, the critical line density of cylinders decreases for increasing levels of irradiation. Also like the spherical case, irradiation is felt more strongly by lower density cylinders; grain size dependence is weak, and silicate grains are less affected by irradiation. The different geometry of spheres and cylinders gives rise to some subtle differences. For instance, \(\Lambda_{\text{crit}}\) is slightly less sensitive to increasing irradiation than is \(M_{\text{crit}}\). Table 2 presents critical line densities of irradiated cylinders for a range of effective temperatures.

4.3 Low-mass star-forming regions

In low-mass star-forming regions, both nearby young stellar objects (YSOs) and the diffuse ISRF contribute to the radiation field. We first consider quiescent regions with no YSOs. Under the ISRF in the Solar vicinity (shaded grey in Fig. 7), the critical mass of a molecular clump \((n_c = 10^3 \text{ cm}^{-3})\) is significantly reduced, to values as small as 5.5 \(M_\odot\), i.e. 40 per cent of the non-irradiated value (see red curves in Fig. 7). On the other hand, the stability properties of dense cores \((n_c > 10^4 \text{ cm}^{-3})\) are only modestly affected by the Solar ISRF (see blue curves in Fig. 7). Thus, while the Solar ISRF...
Figure 7. Critical mass (top), critical size (bottom) of molecular clumps and cores as a function of radiation strength. The left-hand panels show the critical mass and size of clumps, and cores with ice-mantle dust grains. The right-hand panels show the critical mass and size for different chemical compositions of dust grains, while dust size is fixed to be $a = 0.05 \, \mu m$. The effective temperature is fixed to be 10 K in all solutions. The central gas densities, $n_c$, are written in the panels and marked with different colours. Different line styles denote different sizes of dust grain (left-hand panels) and different chemical composition of dust grain (right-hand panels). The greyed area denotes a range of the ISRF strength in the Solar vicinity. The dash–dotted and the double dash–dotted grey lines denote the average ISRF at the molecular ring ($D_G = 4$ kpc) and the Galactic centre, respectively.

does not affect the collapse of dense cores, this level of irradiation can affect the formation of dense cores within less dense clumps.

Closer to the Galactic centre, the ISRF is more intense, around ~9 times stronger in the molecular ring ($D_G = 4$ kpc) compared to the Solar vicinity, and ~50 times stronger at the Galactic centre (Mezger 1990). (These levels of irradiation are marked by dash–dotted and triple dash–dotted lines, respectively, in Fig. 7.) In the inner Galactic regions, the critical sizes and masses of both dense clumps and dense cores may be significantly smaller ($<20$ per cent) than those in the Solar vicinity. At face value, these results favour the formation of lower mass stars in the more intensely irradiated inner Galaxy. On the other hand, competing effects – such as higher temperatures (e.g. Walmsley & Ungerechts 1983; Ao et al. 2013) and extra non-thermal (e.g. magnetic) support – favour higher mass star formation towards the Galactic centre. More detailed models are needed to include these effects self-consistently.

In more evolved regions, molecular clouds receive enhanced irradiation from nearby YSOs, stellar associations or clusters (e.g. NGC 1333, B1688 & B1689 in $\rho$ Ophiuchus, L1495A in Taurus; see Bontemps et al. 2001; Volgenau et al. 2006; Maruta et al. 2010; Seo et al. 2015). Consider a stellar association following Kroupa’s IMF (initial mass function) with $\sim 600$ stars and with the earliest stellar-type being B9V. For a typical cluster diameter of 1 pc (Nilakshi et al. 2002), we roughly and conservatively estimate the radiation field by placing all stars in a 0.5 pc radius shell around a central reference point. A non-ionizing radiation flux of 0.05 erg cm$^{-2}$ s$^{-1}$ would be incident upon an opaque cloud at this reference point. The actual radiation field will, of course, depend on more realistic stellar locations and will be larger and closer to the brightest stars. Fig. 7 shows that this nominal flux of 0.05 erg cm$^{-2}$ s$^{-1}$ is enough to reduce the critical mass of dense cores from $4.4 \sim 3 M_\odot$. This order unity change might not seem significant, given our idealized model. However, the idea that radiation from nearby YSOs could help regulate the IMF merits further discussion, which we begin in the summary.

Irradiation also helps to trigger the formation of starless cores within filamentary structures. A non-irradiated young filament with $n_c \sim 10^3$ cm$^{-3}$ at 10 K should not fragment until it reaches a critical line density of 16.4 $M_\odot$ pc$^{-1}$. However, irradiation by the ISRF in the Solar vicinity can lower the fragmentation threshold to 9 $M_\odot$ pc$^{-1}$ (see grey-shaded area in the left-hand panel of Fig. 8). Irradiation can thus explain why some filaments embed dense cores, despite having line densities below the standard (non-irradiated) critical value (Benedettini et al. 2015). For example, a cold filament in L1495-B218 (no. 28 in Hacar et al. 2013) has a line density of 9.3 $M_\odot$ pc$^{-1}$ but embeds NH$_3$ starless cores (Seo et al. 2015). On the other hand, filaments with high line densities, e.g. in Aquila (Arzoumanian et al. 2011), seem to require extra internal support – e.g. magnetic – to explain their existence beyond nominal stability.

MNRAS 461, 1088–1099 (2016)
Table 1. Critical sizes and masses of dense clumps and cores under radiation.

| \(n_c^0\) (cm\(^{-3}\)) | \(F_0^0\) (erg cm\(^{-2}\) s\(^{-1}\)) | \(\alpha^c\) (\(\mu\)m) | \(T_{\text{eff}}^d = 7.5\) K | Critical size and mass (pc, M\(_\odot\)) at 10 K | Critical size and mass (pc, M\(_\odot\)) at 15 K | Critical size and mass (pc, M\(_\odot\)) at 20 K | Critical size and mass (pc, M\(_\odot\)) at 25 K |
|---|---|---|---|---|---|---|---|
| 0.002 | 0.1 | 0.546, 8.08 | 0.636, 12.6 | 0.789, 23.7 | 0.919, 36.9 | 1.03, 52.0 |
| 0.05 | 0.547, 8.25 | 0.639, 12.9 | 0.742, 22.5 | 0.924, 37.5 | 1.04, 52.7 |
| 0.006 | 0.1 | 0.481, 6.66 | 0.568, 10.7 | 0.716, 20.8 | 0.842, 33.2 | 0.954, 47.4 |
| 0.05 | 0.486, 7.08 | 0.574, 11.4 | 0.633, 18.3 | 0.853, 34.7 | 0.967, 49.4 |
| 0.02 | 0.1 | 0.360, 3.55 | 0.438, 6.25 | 0.572, 13.7 | 0.688, 23.4 | 0.792, 35.2 |
| 0.05 | 0.375, 4.29 | 0.455, 7.60 | 0.461, 9.17 | 0.712, 27.3 | 0.819, 40.4 |
| \(10^3\) | 0.06 | 0.212, 0.853 | 0.267, 1.63 | 0.374, 4.32 | 0.477, 8.44 | 0.570, 15.3 |
| 0.05 | 0.230, 0.978 | 0.303, 2.32 | 0.231, 0.926 | 0.528, 14.5 | 0.622, 23.9 |
| 0.2 | 0.1 | 0.0968, 0.0977 | 0.118, 0.171 | 0.159, 0.396 | 0.201, 0.76 | 0.246, 1.32 |
| 0.05 | 0.0825, 0.0552 | 0.106, 0.109 | 0.0722, 0.0381 | 0.235, 0.941 | 0.327, 2.56 |
| 0.6 | 0.1 | 0.0498, 0.0145 | 0.0590, 0.0239 | 0.0758, 0.0491 | 0.0913, 0.0837 | 0.106, 0.129 |
| 0.05 | 0.0384, 0.006 40 | 0.0464, 0.0109 | 0.0343, 0.0046 | 0.0764, 0.0448 | 0.0921, 0.0748 |
| 0.02 | 0.1 | 0.183, 2.77 | 0.212, 4.29 | 0.261, 7.91 | 0.303, 12.2 | 0.339, 17.1 |
| 0.05 | 0.184, 2.79 | 0.213, 4.31 | 0.262, 7.95 | 0.304, 12.3 | 0.340, 17.2 |
| 0.006 | 0.1 | 0.174, 2.66 | 0.204, 4.14 | 0.253, 7.72 | 0.294, 12.0 | 0.331, 16.8 |
| 0.05 | 0.177, 2.72 | 0.207, 4.22 | 0.256, 7.83 | 0.298, 12.1 | 0.335, 17.0 |
| 0.02 | 0.1 | 0.154, 2.32 | 0.183, 3.72 | 0.231, 7.12 | 0.272, 11.2 | 0.309, 15.9 |
| 0.05 | 0.160, 2.49 | 0.189, 3.94 | 0.239, 7.46 | 0.281, 11.7 | 0.319, 16.5 |
| \(10^4\) | 0.06 | 0.124, 1.63 | 0.150, 2.81 | 0.195, 5.80 | 0.234, 9.53 | 0.270, 13.9 |
| 0.05 | 0.133, 2.01 | 0.161, 3.32 | 0.209, 6.58 | 0.250, 10.6 | 0.287, 15.2 |
| 0.2 | 0.1 | 0.0798, 0.464 | 0.102, 1.09 | 0.141, 3.04 | 0.175, 5.76 | 0.206, 9.14 |
| 0.05 | 0.0944, 1.030 | 0.118, 1.97 | 0.161, 4.55 | 0.198, 7.89 | 0.232, 11.9 |
| 0.6 | 0.1 | 0.0263, 0.0159 | 0.0373, 0.0397 | 0.0732, 0.271 | 0.106, 1.17 | 0.133, 2.74 |
| 0.05 | 0.0472, 0.0725 | 0.0694, 0.383 | 0.106, 1.68 | 0.138, 3.76 | 0.167, 6.51 |

Notes. \(a\) The central density of gas.

\(b\) The radiation flux normal to the dense clump/core surface.

\(c\) The radius of dust grain. The ice-mantle dust grain model is used.

\(d\) The effective temperature of the internal supports including thermal and non-thermal components.

Figure 8. Critical line density of molecular filaments as a function of radiation strength. Left-hand panel shows the critical line densities with ice-mantle dust grains. Right-hand panel show the critical line densities with different chemical composition of dust grains, while dust size is fixed to be \(\alpha = 0.05\) \(\mu\)m. The effective temperature is fixed to be 10 K in all solutions. The central gas densities \(n_c\) are written in the panels and marked with different colours. Different line styles denote different size of dust grain (left) and different chemical composition of dust grain (right). The greyed area denotes a range of the ISRF strength in the Solar vicinity. The dash–dotted and the double dash–dotted grey lines denote the average ISRF at the molecular ring (\(D_G = 4\) kpc) and the Galactic centre, respectively.

thresholds. Thus, a detailed understanding of the physical conditions of a filament – including the radiation environment – is required to determine gravitational stability.

4.4 High-mass star-forming regions

High-mass star-forming regions are strongly affected by radiation from OB associations. Observations preferentially find YSOs near the rims of H ii regions and near globules within H ii regions (Jose et al. 2013). Massive stars can trigger star formation in different ways. In the collect-and-collapse scenario, the stellar winds of massive stars are the trigger (Elmegreen & Lada 1977; Whitworth et al. 1994; Hosokawa & Inutsuka 2005; Dale, Bonnell & Whitworth 2007). In the radiation driven implosion (RDI) scenario, radiation pressure from ionizing photons is responsible (Bertoldi 1989; Lefloch & Lazareff 1994; White et al. 1997;
Kessel-Deynet & Burkert 2003; Chauhan et al. 2009; Gritschneder et al. 2009; Bisbas et al. 2011; Walch et al. 2013).

However, triggered star formation is harder to understand far from the direct influence of stellar winds and ionizing photons. For instance, enhanced YSO populations are observed deep within globules in the ii regions G028.83-0.25 and G041.92+0.04 (Dirienzo et al. 2012). A large-scale compression could play a role. Alternately, we propose that the prodigious non-ionizing radiation, from OB associations, helps to trigger star formation in more embedded regions. Due to a greater penetration depth, non-ionizing radiation will have a greater relative importance compared to ionizing radiation. For instance, in the Gum nebula, cometary globules such as the CG30/31 complex (Nielsen et al. 1998; Kim, Walter & Wolk 2005) and the CG4/Sa101 complex (Rebull et al. 2011) are far from OB associations, but they are near to a stellar association with multiple B- and A-type stars. Similarly, the Cone nebula is a cometary dense cloud embedded within an ii region that is illuminated by Allen’s source (i.e. the B star NGS2264IRS; Thompson et al. 1998).

However, when H ii regions are illuminated by the later-type stars, i.e. OB associations with spectral types later than O6V, non-ionizing radiation will have a greater relative importance compared to ionizing radiation. For instance, in the Gum nebula, cometary globules such as the CG30/31 complex (Nielsen et al. 1998; Kim, Walter & Wolk 2005) and the CG4/Sa101 complex (Rebull et al. 2011) are far from OB associations, but they are near to a stellar association with multiple B- and A-type stars. Similarly, the Cone nebula is a cometary dense cloud embedded within an ii region that is illuminated by Allen’s source (i.e. the B star NGS2264IRS; Thompson et al. 1998). The YSOs in these regions are assumed to be a result of triggered star formation, even though the effects of stellar winds and ionizing radiation are relatively weak. On the other hand, we find that the non-ionizing radiation from nearby stellar associations or the late-type OB associations is strong enough to trigger gravitational collapse by reducing the critical core mass (Figs 7 and 8).

5 MODEL ASSUMPTIONS AND EXTENSIONS

Our study focuses on the role of non-ionizing radiation pressure on dust grains in molecular filaments and cores. Our neglect of ionizing...
radiation is appropriate not only for low-mass star-forming regions but also where ionizing sources are strongly extincted. Similarly, we neglect some radiative forces on dust grains, specifically the photoelectric and photodesorption forces (Weingartner & Draine 2001). These forces – which arise when UV photons remove electrons or atoms, respectively, from the surface of a dust grain – are more important in the diffuse interstellar medium, e.g. in the cold neutral medium, than in the dense molecular regions we consider.

We assume an isotropic background radiation field, where the anisotropy required for a radiation pressure force is introduced by an opaque cylinder or sphere. In reality, the background radiation will be anisotropic, though the ISRF in the Solar vicinity is only asymmetric at the 10 per cent level (Weingartner & Draine 2001). These forces – which arise when UV photons remove electrons or atoms, respectively, from the surface of a dust grain – are more important in the diffuse interstellar medium, e.g. in the cold neutral medium, than in the dense molecular regions we consider.

We neglect rotation, which is probably a weak dynamical effect. Observations of velocity variations across a filament or a dense core indicate that the rotational energy is typically less than 5 per cent of the internal or gravitational energy (e.g. Arquilla & Goldsmith 1986; Goodman et al. 1993; Caselli et al. 2002).

We assume perfect coupling between dust grains and gas, neglecting grain sedimentation. Since radiation pressure dominates gravity at the surface of our objects (for the most adopted irradiation levels), we estimate the terminal speed of dust grains as

\[ v_{\text{terminal}} = \frac{3(Q_{\text{pr}}) F_0}{4 \rho_g c^2}, \]

using the Epstein drag law appropriate for dilute gases (Youdin 2010). The terminal velocity is independent of grain size since radiation pressure and drag forces both scale with the grain cross-section. Fig. 10 shows the terminal velocity and the settling time (across a typical scale of 0.1 pc) versus level of irradiation. The red lines in the plots correspond to the sound speed and sound crossing time. With high levels of irradiation and low gas densities (appropriate near the surface), significant sedimentation could occur. This tendency to settle is counteracted by mixing due to turbulent diffusion or other large scale motions (Youdin & Lithwick 2007). Sedimentation will also be reduced for more optically thin objects that experience flux cancellation. Sedimentation of grains could alter dynamical stability by piling dust grains and concentrating the radiation force in a thin shell, and could also affect observed extinction profiles (Whitworth & Bate 2002). Time-dependent numerical simulations are, likely, required to explore the full effects of grain sedimentation and its dynamical effect on dense structures.

6 SUMMARY AND CONCLUSIONS

We study the gravitational stability of hydrostatic cylinders and spheres bathed in an isotropic, non-ionizing radiation field. We find that the radially inward radiation pressure force promotes – and can trigger – the gravitational collapse of cores and filaments. The classic stability thresholds – the critical mass of BE spheres and the critical line density of isothermal Ostriker cylinders – are significantly lowered once the surface radiation pressure reaches the magnitude of the central gas pressure. Thus, a given level of irradiation more strongly affects objects with a lower central density, provided that the column density is large enough that the optical depth is at least an order unity. Our analysis shows that the critical state of highly irradiated spheres or filaments is characterized by an order unity optical depth. Physically, these highly irradiated objects
must become partially transparent to incident irradiation to avoid implosion. Standard ISRFs are strong enough to influence gravitational stability. For instance, consider a spherical molecular clump with a central density of \( \sim 10^3 \text{ cm}^{-3} \) at 10 K. The maximum stable mass of such an object is 14 M\(_\odot\) without radiation (the BE mass) and only 5 M\(_\odot\) if subject to interstellar irradiation of the Solar vicinity. For more evolved, i.e. denser, cores with central densities \( \sim 10^4 \text{ cm}^{-3} \), a stronger radiation field is needed to affect gravitational stability. These stronger radiation fields can be found towards the Galactic centre or in active star-forming regions near YSOs or stellar associations.

The gravitational stability of molecular filaments is similarly affected by irradiation. A young filament, with a central density of \( \sim 10^5 \text{ cm}^{-3} \) at 10 K, has a maximum line density of 16 M\(_\odot\) pc\(^{-1}\) without radiation, the Ostriker value. Interstellar irradiation in the Solar vicinity can lower the critical line density to only 9 M\(_\odot\) pc\(^{-1}\).

At face value, our results imply that the IMF of stars could vary with the radiation environment. Alternatively, we propose a mechanism to maintain a universal IMF with non-ionizing radiation pressure. Imagine that in some star-forming region there is a temporary over- (or under-) production of massive stars, for either physical or stochastic reasons. Our results show that the resulting enhancement (or reduction, respectively) in irradiation can then reduce (or increase, respectively) subsequent fragmentation masses. The triggering of star formation by the evolving radiation pressure could thus help regulate the IMF.

The full implications of non-ionizing radiation pressure are not yet clear due to neglected effects in our model. Additional support from magnetic fields or strong turbulence will counteract the destabilizing effects of radiation pressure. Furthermore, our static models neglect crucial evolutionary and dynamical effects, notably the processes that set the mass spectrum of prestellar cores. Nevertheless, our results demonstrate that non-ionizing radiation pressure is strong enough to influence both star formation and filamentary structure, so its full implications should be explored in future work.

ACKNOWLEDGEMENTS

We are grateful to J. Serena Kim, Yancy L. Shirley and Kaitlin M. Kratter for stimulating discussions. We thank Bruce Draine for encouragement.

REFERENCES

Alves J. F., Lada C. J., Lada E. A., 2001, Nature, 409, 159
André P. et al., 2010, A&A, 518, L102
André P., Di Francesco J., Ward-Thompson D., Inutsuka S.-I., Pudritz R. E., Pineda J. E., 2014, Protostars and Planets VI. Univ. Arizona Press, Tucson, AZ, p. 27
Ao Y. et al., 2013, A&A, 550, A135
Arquilla R., Goldsmith P. F., 1986, ApJ, 303, 356
Arzoumanian D. et al., 2011, A&A, 529, L6
Bacmann A., André P., Puget J.-L., Abergel A., Bontemps S., Ward-Thompson D., 2000, A&A, 361, 555
Bardeen J. M., 1965, PhD thesis, California Inst. Technol.
Benedettini M. et al., 2015, MNRAS, 453, 2036
Bergin E. A., Tafalla M., 2007, ARA&A, 45, 339
Bertoldi F., 1989, ApJ, 346, 735
Bisbas T. G., Wünsch R., Whitworth A. P., Hubber D. A., Walch S., 2011, ApJ, 736, 142
Bonnor W. B., 1956, MNRAS, 116, 351
Bontemps S. et al., 2001, A&A, 372, 173
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Caselli P., Benson P. J., Myers P. C., Tafalla M., 2002, MNRAS, 327, 251
Chauhan N., Pandey A. K., Ogura K., Ojha D. K., Bhatt B. C., Ghosh S. K., Rawat P. S., 2009, MNRAS, 396, 964
Craspi A., Caselli P., Walmsley M. C., Tafalla M., 2007, A&A, 470, 221
Dale J. E., Bonnell I. A., Whitworth A. P., 2007, MNRAS, 375, 1291
Dirienzo W. J., Indebetouw R., Brogan C., Cyganowski C. J., Churchwell E., Friesen R. K., 2012, AJ, 144, 173
Draine B. T., 2003, ARA&A, 41, 241
Draine B. T., 2011, ApJ, 732, 100
Draine B. T. et al., 2007, ApJ, 663, 866
Ebert R., 1955, ZAp, 36, 222
Ebert R., 1957, ZAp, 42, 263
Elmegreen B. G., Lada C. J., 1977, ApJ, 214, 725
Evans N. J. II, Rawlings J. M. C., Shirley Y. L., Mundy L. G., 2001, ApJ, 557, 193
Gay C. D., Abel N. P., Walter R. L., Stancil P. C., Feierl G. J., Shaw G., van Hoof P. A. M., Williams R. J. R., 2012, ApJ, 746, 78
Getman K. V., Feigelson E. D., Sicilia-Aguilar A., Broos P. S., Kuhn M. A., Friesen R. K., 2012, AJ, 144, 173
Goodman A. A., Benson P. J., Fuller G. A., Myers P. C., 1993, ApJ, 406, 528
Goodman A. A., Barranco J. A., Wilner D. J., Heyer M. H., 1998, ApJ, 504, 223
Greenberg J. M., Li A., 1999, Adv. Space Res., 24, 497
Gritschneder M., Naab T., Burkert A., Heitsch F., 2009, ApJ, 694, L26
Hacar A., Tafalla M., 2011, A&A, 533, A34
Hacar A., Tafalla M., Kaufmann J., Kovács A., 2013, A&A, 554, A55
Hosokawa T., Inutsuka S.-i., 2005, ApJ, 623, 917
Hotzel S., Harju J., Juvela M., 2002, A&A, 395, L5
APPENDIX A: THE DIMENSIONLESS BONNOR STABILITY CRITERION WITH RADIATION PRESSURE

We now show that the dimensionless stability criteria of equation (19) applies even in the presence of radiation pressure, or for that matter any additional spherically symmetric force. The existence of a stability boundary at \( \frac{dm}{ds} = 0 \) can be derived, for instance, from an analysis of the free energy of the system (Stahler 1983). We choose a simpler path and show that the dimensional Bonnor instability condition in physical units, \( \frac{dP}{dV} > 0 \) at fixed mass, remains equivalent to \( \frac{dm}{ds} > 0 \) and thus equation (19).

First, we express the dimensional outer radius, \( r_0 = r(s_0) = \alpha \xi_0 \), in terms of the dimensionless mass, \( m \), as

\[
    r_0 = \frac{GM}{c^2 s_0} m, \quad (A1)
\]

using equation (18).

Next, we consider perturbations to hydrostatic solutions at fixed dimensional mass, \( M \), and temperature, i.e. \( c' \). Equations (18) and (A1) give

\[
    \frac{d \ln(P_0)}{d \ln(r_0)} = 2 \frac{d \ln(m)}{d \ln(r_0)}, \quad (2a)
\]

\[
    \frac{d \ln(r_0)}{d \ln(s_0)} + \frac{1}{2} \frac{d \ln(s_0)}{d \ln(m)} = \frac{1}{2} \frac{d \ln(m)}{d \ln(s_0)} - \frac{d \ln(m)}{d \ln(m)}. \quad (2b)
\]

We can now relate the Bonnor stability criterion to dimensionless variables as

\[
    \frac{d \ln(P_0)}{d \ln(r_0)} = 3 \frac{d \ln(P_0)}{d \ln(r_0)} = \frac{6 \frac{d \ln(m)}{d \ln(s_0)} + \frac{1}{2} \frac{d \ln(m)}{d \ln(m) - \frac{d \ln(m)}{d \ln(s_0)}}}{\frac{d \ln(m)}{d \ln(s_0)}}. \quad (A3)
\]

Thus, a stability transition at \( \frac{dP_0}{dV_0} = 0 \) also gives a transition at \( \frac{dm}{ds_0} = 0 \). The desired sign of the stability criterion for \( \frac{dm}{ds_0} \) requires that the denominator in the final term of equation (A3) be positive.

We verified numerically that this denominator remains positive for our solutions, but a more general argument proceeds as follows. First, note that this denominator is positive for the classic BE solution, as it must be since the correspondence between the stability criteria holds in this case. Next, consider that any finite radiation pressure (or other force) can be increased incrementally from zero to produce a continuous family of solutions that starts with the BE solution (as visualized in Fig. 2). Since none of these incremental steps can produce an infinite divergence in \( \frac{dP_0}{dV_0} \), the denominator in question cannot change sign, and the desired correspondence between dimensionless and dimensional stability criteria holds.

This paper has been typeset from a \TeX/\LaTeX\ file prepared by the author.