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Extreme cosmic ray dominated regions: a new paradigm for high star formation density events in the Universe

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ABSTRACT

We examine in detail the recent proposal that extreme cosmic ray dominated regions (CRDRs) characterize the interstellar medium of galaxies during events of high-density star formation, fundamentally altering its initial conditions (Papadopoulos 2010). Solving the coupled chemical and thermal state equations for dense UV-shielded gas reveals that the large CR energy densities in such systems [$U_{\rm CR} \sim$ few $\times$ (10^3–10^4) $U_{\rm CR,Gal}$] will indeed raise the minimum temperature of this phase (where the initial conditions of star formation are set) from ∼10 K (as in the Milky Way) to ∼50–100 K. Moreover in such extreme CRDRs the gas temperature remains fully decoupled from that of the dust, with $T_{\rm kin} \gg T_{\rm dust}$, even at high densities [$n({\rm H_2}) \sim 10^5$–$10^6\,{\rm cm^{-3}}$], quite unlike CRDRs in the Milky Way where $T_{\rm k} \sim T_{\rm dust}$ when $n({\rm H_2}) \gtrsim 10^5\,{\rm cm^{-3}}$. These dramatically different star formation initial conditions will (i) boost the Jeans mass of UV-shielded gas regions by factors of ∼10–100 with respect to those in quiescent or less extreme star-forming systems and (ii) 'erase' the so-called inflection point of the effective equation of state of molecular gas. Both these effects occur across the entire density range of typical molecular clouds, and may represent *a new paradigm for all high-density star formation in the Universe, with CRs as the key driving mechanism*, operating efficiently even in the high dust extinction environments of compact extreme starbursts. The characteristic mass of young stars will be boosted as a result, naturally yielding a top-heavy stellar initial mass function (IMF) and a bimodal star formation mode (with the occurrence of extreme CRDRs setting the branching point). Such CRDRs will be present in Ultra-Luminous Infrared Galaxies (ULIRGs) and merger-driven gas-rich starbursts across the Universe where large amounts of molecular gas rapidly dissipate towards compact disc configurations where they fuel intense starbursts. In hierarchical galaxy formation models, CR-controlled star formation initial conditions lend a physical basis for the currently postulated bimodal IMF in merger/starburst versus quiescent/disc star-forming environments, while naturally making the integrated galactic IMFs a function of the star formation history of galaxies.

Key words: cosmic rays – ISM: molecules – ISM: supernova remnants – galaxies: interactions – galaxies: starburst – galaxies: star formation.

1 INTRODUCTION

Much of the stellar mass in the Universe forms in starbursts (e.g. Blain et al. 1999; Genzel et al. 2001; Smail et al. 2002), spectacular events during which the star formation rate (SFR) of a galaxy rises from few solar masses per year, typical of spirals such as the Milky Way (Mckee & Williams 1997), to several hundred solar masses per year as in the local ultra-luminous infrared galaxies (ULIRGs) (e.g. Sanders & Mirabel 1996; Genzel et al. 1998; Sanders & Ishida 2004) where merger-driven starbursts take place in very compact ($D \sim 100$–300 pc) dense gas discs (e.g. Downes & Solomon 1998; Sakamoto et al. 2008). In the so-called submm galaxies (SMGs), similarly merger-driven starbursts in the distant Universe, SFRs can even reach thousands of solar masses per year (Smail et al. 1997; Hughes et al. 1998; Eales et al. 1999). While stars form

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invariably out of molecular gas throughout the Universe (e.g. Solomon et al. 1997; Frayer et al. 1998, 1999; Greve et al. 2005, Tacconi et al. 2006), it is in its densest, UV-shielded, and cosmic ray (CR)-dominated phase where the SF initial conditions and the characteristic mass of the emergent young stars $M_{\rm ch}^{(*)}$ are truly set (Bergin & Tafalla 2007; Elmegreen, Klessen & Wilson 2008). Indeed, while photon-dominated regions (PDRs) contain the bulk of the molecular gas mass in galaxies (Hollenbach & Tielens 1999; Ossenkopf et al. 2007), their widely varying physical conditions remain always far removed from those prevailing in UV-shielded CR-dominated dense gas cores. The location of the latter deep inside molecular clouds, a strong temperature regulation via the onset of gas–dust thermal equilibrium at densities $n({\rm H_2}) > 10^4\,{\rm cm^{-3}}$, and the nearly complete dissipation of supersonic turbulence (Jappsen et al. 2005; Larson 2005; Bergin & Tafalla 2007), all help to keep the thermal state of typical CRDRs a near invariant over a wide range of interstellar medium (ISM) environments.

CRs, accelerated in shocks around supernovae remnants or winds associated with O, B star clusters (e.g. Binns et al. 2008), are responsible for the heating, ionization level, and chemical state of such dense UV-shielded regions in molecular clouds (e.g. Goldsmith & Langer 1978; Goldsmith 2001). Moreover, while their heating contribution relative to that from the far-UV (FUV) induced photoelectric effect in PDRs, or turbulence, can vary within a galaxy and individual molecular clouds, CRs remain responsible for setting the *minimum* temperature attainable in the gaseous ISM (e.g. Goldsmith & Langer 1978; Bergin & Tafalla 2007; Elmegreen et al. 2008). For the Galaxy $T_{\rm k}({\rm min}) \sim 10\,{\rm K}$, and is reached in UV-shielded cores with $n({\rm H_2}) \sim (10^4$–$10^6)\,{\rm cm^{-3}}$.

A recent study has shown that the average CR energy densities ($U_{\rm CR}$) in compact starbursts typical in ULIRGs (recently found also in an SMG at $z \sim 2.3$; Swinbank et al. 2010) will be boosted by the tremendous factors of $U_{\rm CR} \sim {\rm few} \times (10^3$–$10^4)\,U_{\rm CR,Gal}$, potentially transforming their ISM into extreme CR-dominated regions (CRDRs). This will dramatically alter the thermal and ionization state of UV-shielded cores, and thus the initial conditions of SF, throughout their considerable molecular gas reservoirs ($\sim 10^9$–$10^{10}\,{\rm M_\odot}$). Higher characteristic mass $M_{\rm ch}^{(*)}$ for the young stars formed in such ISM environments, and longer ambipolar diffusion time-scales for the CR-heated UV-shieled cores could thus be a new paradigm for high-density SF in the Universe (see Papadopoulos 2010, for details). It is worth mentioning that recently such large $U_{\rm CR}$ boosts ($\sim 10^{3.5} \times U_{\rm CR,Gal}$) have been found in the Orion A bar, and while not representing the average SF initial conditions in the Galaxy, they do allow local studies of the effects of large CR energy densities on the ISM (Pellegrini et al. 2009). Finally CRs have been shown to affect the thermal state of primordial gas, catalyzing H_2 formation in the absence of dust (Jasche, Ciardi & Ensslin 2007).

In this work we solve the coupled chemical and thermal state equations for UV-shielded gas and its concomitant dust in extreme CRDRs without the approximations employed by Papadopoulos (2010). We then use the thermal states computed for such a gas phase to examine the effects on $M_{\rm ch}^{(*)}$ and the so-called inflection point of the effective equation of state (EOS), set at gas densities above which $T_{\rm kin} \sim T_{\rm dust}$ (e.g. Spaans & Silk 2000; Larson 2005 and references therein). Both of these play a crucial role in determining the stellar initial mass function (IMF) in galaxies, which could thus turn out to be very different in the CRDRs of extreme starbursts. Throughout this work we make the standard assumption of $U_{\rm CR} \propto \dot{\rho}_{\rm sfr}$ (SFR *density*) as in Papadopoulos (2010), though we now discuss possible caveats (Section 4.4). Finally, the different IMFs expected in extreme CRDRs will modify the total SFR and $\dot{\rho}_{\rm sfr}$ values computed in galaxies (from e.g. cm non-thermal or IR thermal continuum). In this new context and throughout this work, SFR and $\dot{\rho}_{\rm sfr}$ will now denote these quantities only for the massive stars (which define $U_{\rm CR}$ and power the IR/cm continuum of the ISM), with their total values necessarily remaining uncertain, depending on the exact IMF, which will no longer be an invariant.

2 THE MINIMUM GAS TEMPERATURE IN CRDR

In this section we compute the equilibrium gas temperatures for the UV-shielded regions of molecular clouds immersed in the large CR energy densities of the extreme CRDRs expected in starbursts with high-SFR densities.

2.1 A simple method

We first consider the simple case where the chemical state of the UV-shielded dense gas cores remains unaltered and the only effect of large $U_{\rm CR}$ values is to heat them much more than in quiescent ISM environments. Following standard practice (e.g. Goldsmith 2001), the temperature of such regions can be estimated from the thermal balance equation:

$$\Gamma_{\rm CR} = \Lambda_{\rm line} + \Lambda_{\rm gd}, \qquad (1)$$

where $\Gamma_{\rm CR} \propto \zeta_{\rm CR}\, n({\rm H_2})$ is the CR heating with $\zeta_{\rm CR} \propto U_{\rm CR}$ being the CR ionization rate. The cooling term $\Lambda_{\rm line}$ is dominated by CO and other molecular lines, while $\Lambda_{\rm gd}$ accounts for gas cooling due to the gas–dust interaction.

A significant point of departure from the previous analysis by Papadopoulos (2010) is the inclusion of the atomic fine structure lines O I (at 63 μm) and C II (at 158 μm) in $\Lambda_{\rm line}$. Indeed for the CR-boosted temperatures expected in the UV-shielded dense gas of extreme CRDRs, and unlike the corresponding gas phase in the quiescent ISM of the Galaxy, the cooling from the fine structure atomic line of O I (63 μm) can also become important and along with the gas–dust interaction overtake the CO lines for typical core densities of $n({\rm H_2}) \geq 10^5\,{\rm cm^{-3}}$ when $T_{\rm k} > 50\,{\rm K}$. Finally, ISM–CR interactions can generate internal UV radiation which destroys CO, producing traces of C II, thus cooling via its fine structure line at 158 μm must also be included. The thermal balance equation encompassing all physical processes that can be important in the UV-shielded ISM of extreme CRDRs thus is

$$\Lambda_{\rm CO}(T_{\rm k}) + \Lambda_{\rm gd}(T_{\rm k}, T_{\rm dust}) + \Lambda_{\rm O\,I\,63}(T_{\rm k}) + \Lambda_{\rm C\,II}(T_{\rm k}) = \Gamma_{\rm CR}, \qquad (2)$$

(for the expressions used, see Appendix A). The solutions are shown in Fig. 1, from where it becomes obvious that the minimum temperatures attainable in dense gas cores in the ISM of such starbursts are much higher than in the Galaxy or galaxies with moderate $\dot{\rho}_{\rm SFR}$ values. Turbulent gas heating was not considered since we want to compute the minimum temperature values for UV-shielded gas and since supersonic turbulence (and thus shock-heating) has usually dissipated in dense pre-stellar gas cores where the initial conditions of SF are set.

From Fig. 1 it can be seen that the minimum gas temperatures possible in extreme CRDRs are lower than those computed by Papadopoulos (2010), a result of the extra cooling power emanating from the now included atomic transitions that become excited at the high temperatures now possible in an ISM permeated by large CR energy densities. Nevertheless these minimum possible gas temperatures remain ∼5–10 times higher in extreme CRDRs than those in the Milky Way or galaxies with moderate $\dot{\rho}_{\rm SFR}$ values. Any IR

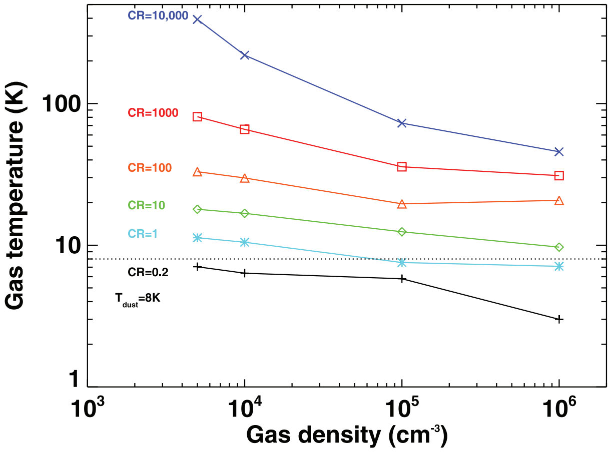

Figure 1. The temperature of UV-shielded dense gas cores computed from equation (2) for the range of densities typical in molecular clouds. The CR energy densities range from the quiescent environment of the Galaxy [$U_{\rm CR} = (0.2\text{–}1) \times U_{\rm CR,Gal}$] to those in extreme CRDRs [$U_{\rm CR} \sim (10^3\text{–}10^4) \times U_{\rm CR,Gal}$; Papadopoulos 2010]. A dust temperature $T_{\rm dust} = 8$ K and a Galactic CR ionization rate of $\zeta_{\rm CR} = 5 \times 10^{-17}\,{\rm s}^{-1}$ have been assumed.

radiation 'leaking' deep in the cloud and warming the concomitant dust above ∼(8–10) K or any remnant turbulent gas heating (Pan & Padoan 2009) can only raise these minimum temperatures further.

2.2 Solving for the coupled chemical and thermal state of UV-shielded gas cores in extreme CRDRs

The thermal balance equation for UV-shielded, CR-heated gas (equation 2) and its solutions (Fig. 1), while physically transparent, do not account for the fact that ISM chemistry (and thus the abundance of coolants) is also strongly CR-regulated in such regions . This makes the problems of thermal and chemical balance of CR-dominated gas strongly coupled that must be solved together, especially given the very large CR energy densities possible in the CRDRs of compact starbursts. We do so by utilizing the advanced time-dependant UCL –PDR code (the latest version described in Bell, Viti & Williams 2007) to compute gas temperatures of CR-heated molecular cloud interiors self-consistently with their CR-regulated chemistry for a wide range of CR energy densities. This model has already been successfully used several times to model PDRs in the Galaxy (e.g. Thi et al. 2009).

The heating mechanisms included are (i) photoelectric effect from silicate grains and polycyclic aromatic hydrocarbons (PAHs), (ii) H_2 formation on gain surfaces, (iii) H_2 photodissociation, (iv) H_2 UV fluorescence, (v) C II recombination and (vi) interaction of low-energy CRs with the gas. The latter dominate gas heating deep inside H_2 clouds ($A_{\rm v} \geq 5$) where dense gas cores reside and the initial conditions for SF are set. At cloud surfaces hot gas emits Lyα and O I (63 μm) lines while deeper in ($A_{\rm v} > 0.1$), gas cooling occurs via fine-structure line emission of oxygen and neutral and singly ionized carbon. Vibrational and ro-vibrational lines of H_2 and CO also cool the gas while CO rotational lines are excellent coolants for the cold inner regions as the first rotationally excited level reaches down to 5.5 K. The interaction between the gas and the dust grains acts as cooling or heating agent for the gas depending on the difference between the gas and dust temperature. H_2 and CO self-shielding are taken into account. The code calculates the gas chemical abundances, emergent cooling line fluxes and temperatures self-consistently at each depth in the cloud, and it has been benchmarked against other state-of-the art photodissociation region codes in Röllig et al. (2007).

We set a nominal incident FUV field of $G_0 = 1$ in Habing units (expected to be even lower for the dense pre-stellar cores deep inside H_2 clouds) and a residual micro-turbulent linewidth of $\Delta V_{\rm m\text{-}turb} = 5\,{\rm km\,s^{-1}}$ (which enters the expressions of line optical depths). In all cases chemical and thermal equilibrium is reached fast, within $T_{\rm chem,th} \leq 10^4$ yr, and is always shorter than the local dynamical time-scale which drives the ambient SF events and thus the temporal evolution of $U_{\rm CR}$. The results, shown in Fig. 2, corroborate the high gas temperatures obtained using the simpler method. This reveals the CRs as *the most important feedback aspect of SF* capable of significantly altering its initial conditions during events of high SF density via the strong heating of the deeply embedded and UV-shielded dense gas regions of molecular clouds. It can thus operate unhindered in the high dust extinction environments of extreme starbursts such as local ULIRGs or high-redshift SMGs.

2.2.1 *Testing the results for stronger radiation fields*

We also ran the same grid of models with the incident FUV radiation field scaling exactly as the CR energy densities which correspond to the maximum incident radiation field that can be expected for dense gas cores (in practice pre-stellar cores are always UV-shielded deep inside molecular clouds). The dust temperature is now more important than in the previous case of $G_0 = 1$, and is computed as part of the code. Its value inside the cloud can influence the cooling by emitting IR photons which interact with line radiative transfer, the H_2 formation by changing the sticking probability, the evaporation/condensation of molecules and most importantly the gas–grain heating/cooling. The UCL-PDR code uses a modified version of the formula of Hollenbach, Takahashi & Tielens (1991, hereafter HTT) corrected for the various mean grain sizes.

The HTT formula has been further modified to include attenuation of the far-IR (FIR) radiation. The incident FUV radiation is absorbed and re-emitted in the IR by dust at the surface of the cloud (up to $A_{\rm v} \sim 1$ mag). In the HTT derivation, this FIR radiation then serves as a second heat source for dust deeper into the cloud. However in their model, this secondary radiation component is not attenuated with distance into the cloud, remaining undiminished with depth and leading to higher dust temperatures deep into the cloud, which in turn heats the gas to unrealistic temperatures. Attenuation of the FIR radiation has been introduced by using an approximation for the IR-only dust temperature from Rowan-Robinson (1980); his equation (30b): $T = T_\circ (r/r_0)^{-0.4}$, where r_0 is the cloud depth corresponding to $A_{\rm v} = 1$ mag outer 'slab' that processes the incident FUV radiation and then re-emits it in the FIR.

From Fig. 3, it can be readily seen that the gas temperatures remain invariant beyond $A_{\rm v} \sim 5$ even with incident FUV fields as enhanced as the CR energy densities. This essentially leaves CRs *as the only strong feedback factor of SF operating efficiently deep inside molecular clouds.* Moreover, intense CR heating of UV-shielded gas strongly decouples gas and dust temperature even at high densities (Figs 1, 2, 3) with important implications on the gas fragmentation properties and thus on the emergent stellar IMF (Section 3.2).

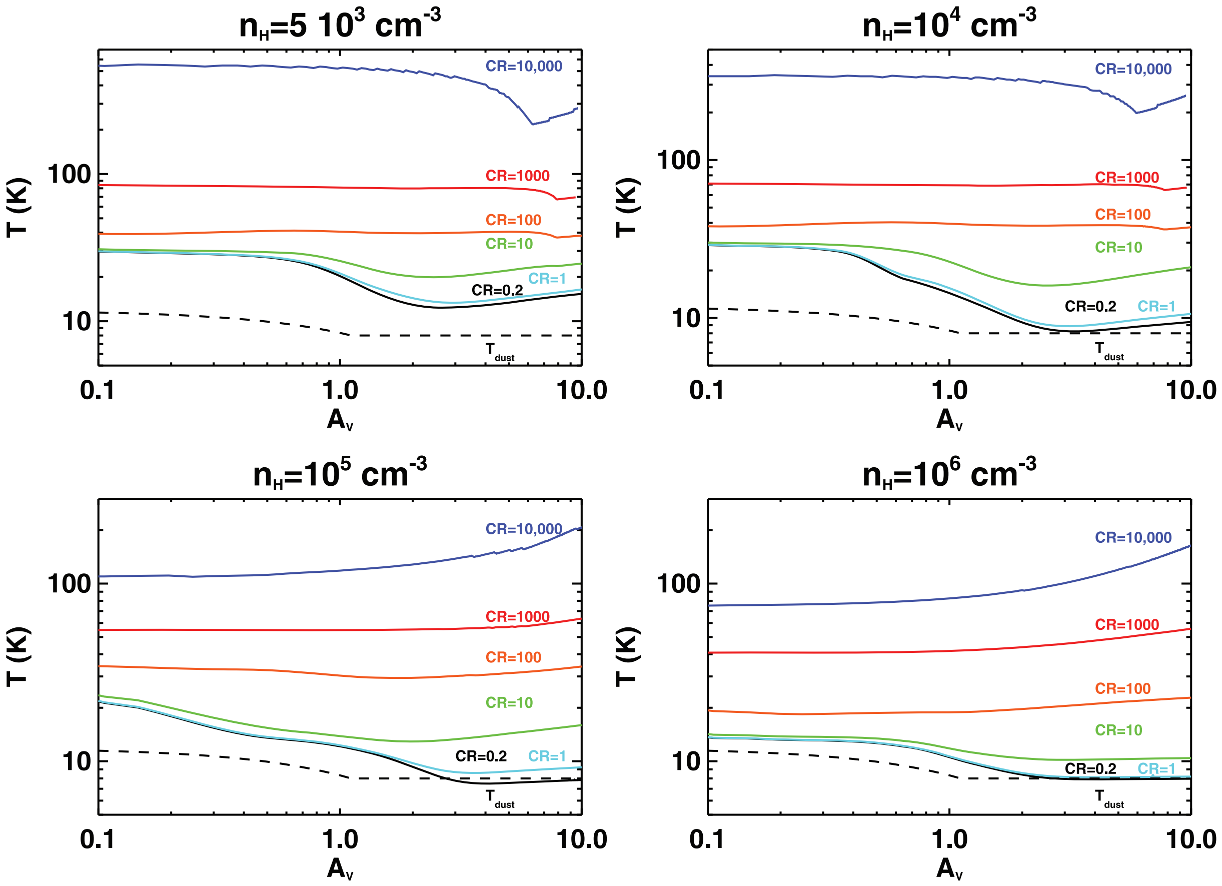

Figure 2. The gas temperature profiles versus optical extinction inside molecular clouds immersed in a range of CR energy densities, estimated using the time-dependant UCL-PDR code solving both for thermal and chemical equilibrium at each point of the cloud. The CR energy densities range from Galactic values $\sim (0.2\text{–}1) \times U_{\rm CR,Gal}$, to low-level star-forming systems $\sim 10 \times U_{\rm CR,Gal}$, and extreme starbursts $\sim (10^3\text{–}10^4) \times U_{\rm CR,Gal}$. The densities encompass the range typical for star-forming molecular clouds, and the incident FUV field assumed is $G_0 = 1$ (in Habing units). The dust temperature $T_{\rm dust}(A_{\rm v})$ profile is indicated by the dashed black line. Stronger radiation fields reaching the dense pre-stellar cores deep inside molecular clouds (e.g. because of 'leaking' FUV radiation from O, B stars inside the typically clumpy molecular ISM) can further raise the gas temperatures for $A_{\rm v} \le 5$, while deeper than that gas temperatures remain always CR-controlled. The small ∼10 per cent rise of $T_{\rm k}(A_{\rm v})$ at the highest densities and $U_{\rm CR}$ values for $A_{\rm v} \gtrsim 5$ is likely an artefact of the high optical depths of C and CO at such large cloud depths (see Bayet et al. 2010).

3 NEW INITIAL CONDITIONS FOR STAR FORMATION, AND THE STELLAR IMF IN EXTREME CRDR

The new detailed thermochemical calculations presented here support the results from the previous study of CRDRs and the effects of high $U_{\rm CR}$ values on the initial conditions of SF (Papadopoulos 2010). The thermal state of UV-shielded dense gas is indeed dramatically altered in the CRDRs of extreme starbursts, and this will affect its Jeans mass, gas fragmentation properties and the characteristic mass $M^{(*)}_{\rm ch}$ of young stars. This contradicts the results by Elmegreen et al. (2008) which, while correctly considering the UV-shielded gas phase as the one where the SF initial conditions are set, omitted CRs from its thermal balance.

It must be pointed out that while several other studies investigated the effects of starburst environments on the IMF, all (besides the one by Elmegreen et al. 2008) failed to consider the ISM phase where the initial conditions of SF are actually set (the CRDRs). Instead they used physical properties typical of PDRs (e.g. Klessen, Spaans & Jappsen 2007) which, while dominating the observed dust spectral energy distributions (SEDs) and molecular line SEDs (SLEDs) of galaxies, they are hardly representative of the physical conditions expected in their CRDRs. Even for mildly SF IR-luminous galaxies, the dust temperature typical of their global SEDs is ∼(30–40) K, which is well above $T_{\rm dust} \sim (8\text{–}10)$ K expected in their CRDRs. Using inappropriate PDR-type initial conditions of SF in numerical models (i) would make them hard-pressed to account even for the near-invariant IMF found in the Galaxy (as the wide range of physical conditions in its massive PDR gas phase would yield a wide range of IMFs), (ii) omits the significant, CR-induced, thermal decoupling between gas and dust (Figs 2 and 3). The latter fundamentally impacts the so-called inflection point of effective EOS used in all realistic (i.e. non-isothermal) numerical simulations of molecular cloud fragmentation (e.g. Jappsen et al. 2005; Bonnell, Clarke & Bate 2006), and this is further discussed in Section 3.2.

3.1 The characteristic mass of young stars in CRDRs

The thermal state of these dense pre-stellar gas cores is no longer a near-invariant but is instead strongly altered by the high CR energy density backgrounds of extreme starbursts, inevitably affecting the fragmentation of those gas regions towards protostars. Indeed, the

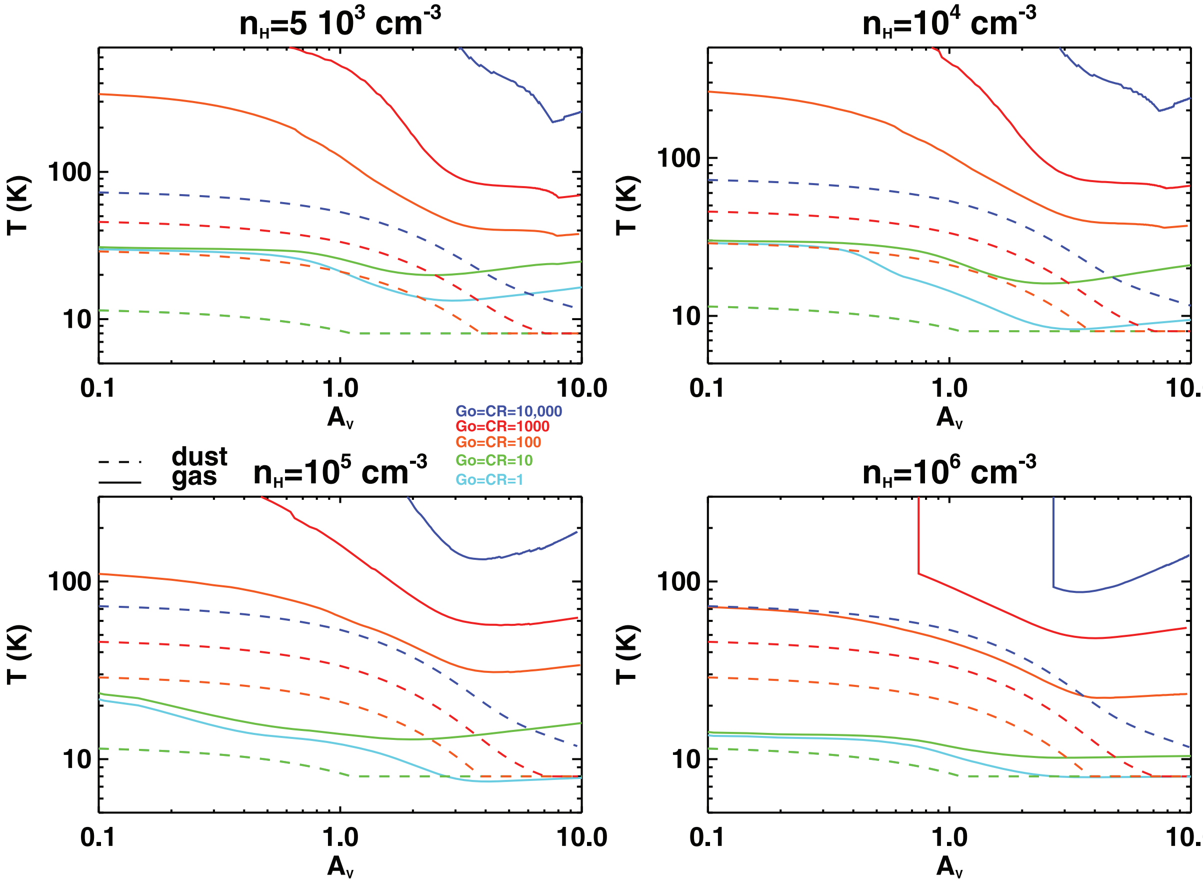

Figure 3. The computed gas and dust temperature profiles versus optical extinction inside molecular clouds as in Fig. 2, but now with the incident FUV radiation field also scaling as the CR energy density. The now strongly varying dust temperatures are shown along with the gas temperatures as dashed lines with the same colour. The gas temperatures at $A_v = 5$–10 remain almost invariant (compare with Fig. 2) demonstrating the near-invariance of the thermal state of the gas (and thus of the SF initial conditions) deep inside molecular clouds when it comes to its dependence on the radiation field. The abrupt T_k drop at high densities [$\sim(10^5$–$10^6)\,\mathrm{cm}^{-3}$] and G_0 values is due to a lack of atomic/ion coolants in the H-rich region; as H is converted into H_2, the H_2 formation heating (which was the major heating agent) drops while at the same time C I cooling (C II is converted to C I due to H_2/C mutual shielding) and H_2 cooling sharply increase. For high U_{CR}, the gas remain much warmer than the dust, marking a *CR-induced thermal decoupling of gas and dust* (Section 3.2).

Jeans mass for such CR-heated cores,

$$M_J^{(c)} = \left(\frac{k_B T_k}{G\mu m_{H_2}}\right)^{3/2} \rho_c^{-1/2}$$
$$= 0.9\left(\frac{T_k}{10\,\mathrm{K}}\right)^{3/2}\left[\frac{n_c(H_2)}{10^4\,\mathrm{cm}^{-3}}\right]^{-1/2} \mathrm{M}_\odot, \qquad (3)$$

rises from $M_J^{(c)} \sim 0.3\,\mathrm{M}_\odot$ when $n_c(H_2) = 10^5\,\mathrm{cm}^{-3}$ and $T_k = 10\,\mathrm{K}$ (typical for the Galaxy), to $M_J^{(c)} \sim (3$–$10)\,\mathrm{M}_\odot$ for $T_k \sim (50$–$110)$ K expected for same density H_2 gas immersed in the very large CR energy densities of extreme starbursts. The near-invariance of $M_J^{(c)}$ in galaxies (Elmegreen et al. 2008) is thus upended in starbursts with high SFR densities. In Fig. 4 the M_J values computed for molecular gas immersed in the CRDRs of compact extreme starbursts are shown for a gas density range typical for star-forming molecular clouds. For $U_{CR}/U_{CR,Gal} \geq 10^3$, M_J increases by a factor of $\sim$10 across the entire range, which will invariably lead to a higher $M_{ch}^{(*)}$ and thus a top-heavy IMF (Larson 2005; Elmegreen et al. 2008). The wide range of densities over which this occurs makes this conclusion independent of the specific details of molecular cloud fragmentation as long as $M_J[n(\boldsymbol{r}, t), T_k(\boldsymbol{r}, t)]$ drives the fragmentation process outcome at each spatial and temporal point $(\boldsymbol{r}, t)$. The latter is the current consensus on the role of the Jeans mass in molecular cloud fragmentation towards a stellar IMF, though the views regarding the particular gas phase whose M_J sets the $M_{ch}^{(*)}$ vary (e.g. Klessen 2004; Bonnell et al. 2006).

If $M_{ch}^{(*)} \propto \langle M_J \rangle$ at the *onset* of molecular cloud fragmentation (Klessen 2004), the CR-boost of $M_{ch}^{(*)}$ in extreme CRDRs is obvious from the large vertical displacement of the M_J values in Fig. 4. In a non-isothermal gravoturbulent molecular cloud fragmentation scheme (e.g. Jappsen et al. 2005), it is $M_{ch}^{(*)} \sim M_J(n_c)$ at a characteristic gas density n_c above which efficient gas–dust thermal coupling lowers the gas temperature in CRDRs towards a minimum value of $T_k(\mathrm{min}) \sim T_{dust}$ (Larson 2005). For the Galaxy this occurs at $n_c \sim 10^5\,\mathrm{cm}^{-3}$, a density that marks also the transition to near-isothermal cloud regions where thermal motions dominate over supersonic turbulence (Larson 2005; Bergin & Tafalla 2007). From Figs 2 and 3, it is obvious that the high CR energy densities in extreme CRDRs *will keep the gas and dust thermally decoupled, with* $T_k(\mathrm{min}) \gg T_{dust}$, and thus a characteristic density can no longer be marked by the onset of thermal equilibrium between gas and dust. Such CR-induced effects have been long suspected for the dense molecular gas in the Galactic Centre (GC; Yusef-Zadeh, Wardle & Roy 2007).

In the CR-inundated molecular clouds of extreme starbursts, a characteristic density in the ISM can now remain only as the one where the supersonic turbulence has fully dissipated and overtaken

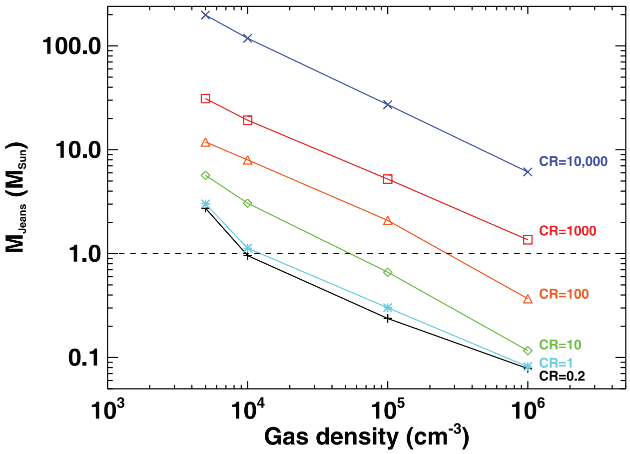

Figure 4. The Jeans mass estimated from equation (3) and gas temperatures inside CRDRs, computed for the corresponding densities (using the full UCL-PDR code) and averaged over the inner $A_{\rm v} = 5$–10 cloud regions (Fig. 2). Low-mass star formation will be clearly suppressed in extreme CRDRs for a $M_{\rm J}$-driven gas fragmentation towards a stellar IMF (see text).

by thermal motions in pre-stellar cores, a prerequisite for their efficient gravitational collapse (e.g. Krumholz & McKee 2005). The average density of such transition regions can be estimated from two well-known scaling relations in molecular clouds: $\sigma_{\rm V}(r) = \sigma_0(r/pc)^h$ (linewidth-size) and $\langle n\rangle = n_0(r/pc)^{-1}$ (density-size) after setting $\sigma_{\rm V}({\rm min}) = (3k_{\rm B}T_k/\mu m_{\rm H_2})^{1/2}$ as the minimum linewidth possible, and solving for the corresponding mean volume density:

$$\langle n_{\rm tr}\rangle = n_0\left(\frac{\mu m_{\rm H_2}\sigma_0^2}{3k_{\rm B}T_{\rm k}}\right)^{1/2h} \sim 11n_0\left(\frac{\sigma_0}{\rm km\,s^{-1}}\right)^2\left(\frac{T_{\rm k}}{10\,{\rm K}}\right)^{-1}. \qquad (4)$$

For $h = 1/2$ (expected for gas clouds virialized under external pressure; Elmegreen 1989), $\sigma_0 = 1.1\,{\rm km\,s^{-1}}$ and for $n_0 =$ few $\times\ 10^3\,{\rm cm^{-3}}$, it is $\langle n_{\rm tr}\rangle \sim$ few $\times\ 10^4\,{\rm cm^{-3}}$. For the CR-boosted gas temperatures in extreme starbursts where typically $T_{\rm k}({\rm min}) \sim 100\,{\rm K}$ (Figs 1, 2, 3), $\langle n_{\rm tr}\rangle \sim$ few $\times\ 10^3\,{\rm cm^{-3}}$ and the (turbulent gas)→(thermal core) transition will occur at lower densities *as well as* higher (CR-boosted) gas temperatures than in quiescent CRDRs. This will then shift the expected $M^{(*)}_{\rm ch}$ both vertically (higher temperatures) as well as to the left (lower densities) of Fig. 4, yielding even higher $M^{(*)}_{\rm ch}$ values than those resulting from only a vertical shift of $M_{\rm J}$ because of CR-boosted gas temperatures.

Thus irrespective of molecular cloud fragmentation details, *a much larger characteristic mass of young stars is expected in the CR-inundated molecular clouds of extreme starbursts.* However the exact shape and mass scale of the new stellar IMF can only be determined with dedicated molecular cloud fragmentation simulations that make use of the new SF initial conditions in extreme CRDRs, along with an EOS appropriate for the very different thermal and ionization state of their molecular gas.

3.2 CRDRs: SF initial conditions and the EOS inflection point

The importance of the effective EOS, parametrized as a polytrope $P = K\rho^{\gamma}$, in the fragmentation properties and emergent mass spectrum of turbulent self-gravitating gas has been well documented in a few seminal papers (Li, Klessen & McLow 2003; Jappsen et al. 2005; Bonnell et al. 2006; Klessen et al. 2007) revealing a crucial role for γ in defining the shape of the collapsed gas core mass distribution (and hence the stellar IMF). The EOS, its polytropic index γ as a function of density, and their dependance on ISM properties such as metallicity and physical conditions such as the elevated cosmic microwave background at high redshifts have also been well documented (Spaans & Silk 2000, 2005), with the so-called EOS inflection point emerging as a general characteristic. In an EOS that seems well approximated by a piecewise polytrope with two distinct γ values, the latter is simply the characteristic density $n_{\rm c}$ for which $\gamma < 1$ when $n < n_{\rm c}$, and $\gamma \gtrsim 1$ for $n \gtrsim n_{\rm c}$. Its crucial role in determining the IMF mass scale, discussed briefly in Section 3.1, is documented throughout the literature (Larson 2005; Jappsen et al. 2005; Elmegreen et al. 2008). In starburst environments, a 'sharpening' of that inflection point is thought to occur because of warm dust. There γ reaches up to ∼1.4 and stays above unity for densities past the inflection point $n_{\rm c} \sim (10^4$–$10^5)\,{\rm cm^{-3}}$ (Spaans & Silk 2005), which suppresses molecular cloud fragmentation while 'tilting' it towards top heavy IMFs (e.g. Li et al. 2003; Klessen et al. 2007).

Unfortunately PDR-like ISM has been used to set the SF initial conditions for starbursts in all of the aforementioned models, even though the dust in CRDRs (where these conditions are really set) remains cool, much lower than the gas, especially in extreme CRDRs. This insensitivity of the CRDR dust temperatures to the ambient FUV radiation field can be demonstrated analytically by simply considering the location of CRDRs deep inside FUV-illuminated molecular clouds at $A_{\rm v} \gtrsim 5$ (e.g. McKee 1989). Then $T_{\rm dust,SB}/T_{\rm dust,Gal} \sim [\exp(-A_{\rm v}/1.086) \times G_{\circ,{\rm SB}}/G_{\circ,{\rm Gal}}]^{1/(4+a)}$ will be the radiation induced boost of the CRDR dust temperature in starbursts $T_{\rm dust,SB}$ with respect to that in the quiescent Galactic environments $T_{\rm dust,Gal} \sim 8\,{\rm K}$. For a dust emissivity law of $\alpha = 2$, a large enhancement of the FUV radiation field $G_{0,{\rm SB}}/G_{0,{\rm Gal}} = 10^4$, and $A_{\rm v} = 5$ it is $T_{\rm dust,SB}/T_{\rm dust,Gal} = 2.15$, yielding $T_{\rm dust} \sim 17\,{\rm K}$, in good agreement with the detailed dust temperature profiles past $A_{\rm v} \sim 5$ shown in Fig. 3. It is actually this robustness of dust temperatures inside CRDRs, along with a strong gas–dust coupling at high densities (when $U_{\rm CR}$ values are modest), that helps retain the thermal states of the pre-stellar gas cores, the $M^{(*)}_{\rm ch}$ values and the IMF, as near invariants over a wide range of ambient PDR conditions (Elmegreen et al. 2008).

Thus PDR conditions, while always dominating the observed dust SEDs and molecular SLEDs of even mildly SF galaxies (as PDRs are warm *and* contain the bulk of the ISM mass), *are not representative of the SF initial conditions in galaxies,* which are set in CRDRs. This leaves the pre-stellar gas phase in them, amounting to a few per cent of the mass per giant molecular cloud (∼SF efficiency per typical GMC), yet to be explored in terms of its EOS and fragmentation properties. A detailed exploration of those in CRDRs will be the subject of a future paper, but Figs 2 and 3 already showed that CRs, by inducing a strong decoupling of the gas and dust temperatures with $T_{\rm k} \gg T_{\rm dust}$, 'erase' any putative EOS inflection point for gas densities up to $n = 10^6\,{\rm cm^{-3}}$. This will maintain efficient molecular gas cooling, with cooling times always much shorter than dynamical times (Fig. 5), and $\gamma < 1$ in CRDRs over the entire gas density range explored here. In such regions, gas gravoturbulent fragmentation will then occur equally efficiently from $n \sim 5 \times 10^3\,{\rm cm^{-3}}$ up to $\sim 10^6\,{\rm cm^{-3}}$ yielding a pure power-law IMF (Spaans & Silk 2000; Li et al. 2003).

The latter result along with our discussion in Section 3.1 makes it clear that the stellar IMF will be very different in extreme CRDRs, though only detailed gravoturbulent simulations with the appropriate initial conditions and performed with a new suitable EOS can decide its exact shape and mass scale. It must be also noted that the very high ionization fractions in extreme CRDRs can now 'anchor' the magnetic field for much longer periods and at much

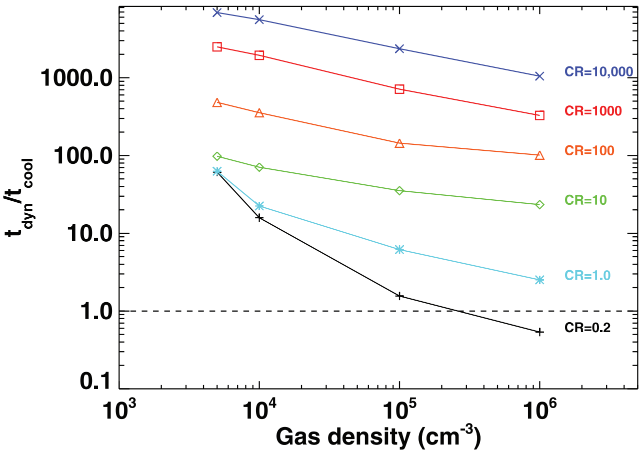

Figure 5. The ratio of dynamical/cooling time-scales in UV-shielded molecular gas of CRDRs ($A_{\rm v} = 5$–10) estimated using the UCL-PDR code and CR energy densities ranging from those expected in quiescent Galactic to compact extreme starbursts.

higher densities, as ambipolar diffusion in such regions is now much prolonged (Papadopoulos 2010). Magnetic fields may thus remain important during much later stages of gas fragmentation, even in a highly turbulent medium, and may thus have to be included in the simulations of this process in extreme CRDRs.

4 CONSEQUENCES, OBSERVATIONAL PROSPECTS

The current study supports the recently suggested role of CRs as a decisive SF feedback factor, capable of altering the SF initial conditions and the IMF in extreme CRDRs. In this section we discuss some of the consequences beyond the immediate issues of the ISM and the stellar IMF in such environments, and outline current and future observations that can shed light on these new SF initial conditions that will be typical in high SFR density events in the Universe.

4.1 A sequence of $\dot{\rho}_{\rm SFR}$-dependent stellar IMFs

The dependance of the thermochemical and ionization state of pre-stellar dense gas in CRDRs on the average $U_{\rm CR}$ permeating the ISM of a galaxy naturally links the SF initial conditions and the resulting IMF to the average SFR density $\dot{\rho}_{\rm SFR}$, provided $U_{\rm CR} \propto \dot{\rho}_{\rm SFR}$. The details of CR transport/escape mechanisms in quiescent SF discs and starbursts will define the proportionality factor (see Suchkov et al. 1993, for details). Thus, once simulations of molecular gas fragmentation in CRDRs produce libraries of the corresponding IMFs, these will be naturally parametrized by $\dot{\rho}_{\rm SFR}$, and hence actual observables (especially in the upcoming era of high-resolution imaging at submm wavelengths with the Atacama Large Millimeter Array, ALMA).

4.2 Implications for hierarchical galaxy formation models: a physically motivated IMF bimodality

In hierarchical galaxy formation models, a bimodal IMF, top-heavy for mergers/starbursts and regular for disc/regular-SF systems, has been postulated to explain the populations of the starbursting/merger-driven SMGs and regular SF discs like the Lyman break galaxies at high redshifts in Λ cold dark matter (ΛCDM) cosmology (Baugh et al. 2005). The CR-controlled SF initial conditions in galaxies, unhindered by dust extinction, can now set this on a firm physical basis. From Figs 2 and 4, it is obvious that for typical SF discs [$U_{\rm CR} \sim (0.2$–$10) \times U_{\rm CR,Gal}$] no substantial effects on the gas temperatures and Jeans masses in CRDRs are expected while in the extreme CDRDs of compact starbursts [$U_{\rm CR} \sim (10^3$–$10^4) \times U_{\rm CR,Gal}$] very warm gas and large Jeans masses will lead to an effective suppression of low-mass SF and hence a top-heavy IMF. For merger-driven SF the latter may characterize entire star-forming episodes (i.e. until the *in situ* molecular gas reservoir is nearly exhausted) as dissipation can continuously 'funnel' the large molecular gas masses of the progenitors towards very compact ($\sim$100–500 pc) regions where extreme, Eddington-limited SF takes place with tremendous IR brightness of $\sigma_{\rm IR} \sim ({\rm few}) \times 10^{13}\,{\rm L}_{\odot}\,{\rm kpc}^{-2}$ (e.g. Thompson 2009). Such high IR brightness, and thus high SFR densities, have been recently deduced also in a distant SMG (Swinbank et al. 2010).

Thus CR-controlled SF initial conditions naturally yield a bimodal SF process in galaxies, with high $\dot{\rho}_{\rm SFR}$ values providing the branching point, as follows:

(merger-driven SF)→(high $\dot{\rho}_{\rm SFR}$)→(high $U_{\rm CR}$)→(top heavy IMF),
(regular disc SF)→(low $\dot{\rho}_{\rm SFR}$)→(low $U_{\rm CR}$)→(Galactic IMF).

This proposed $\dot{\rho}_{\rm SFR}$–IMF link can then parametrize such an SF bimodality in hierarchical galaxy formation, once IMF = F($\dot{\rho}_{\rm SFR}$) 'libraries' are obtained from e.g. gravoturbulent simulations of molecular cloud fragmentation for a range of $\dot{\rho}_{\rm SFR}$ values.

A top-heavy IMF in high-$\dot{\rho}_{\rm SFR}$ systems will have very serious implications on the actual SFRs deduced from the IR luminosities of these typically very dust enshrouded systems (where all the FUV light from massive stars is reprocessed into IR). Their CR-induced top-heavy IMFs will now correspond to several times higher energy outputs per stellar mass, and the SFRs in such systems will have to be revised downwards by identical factors.

4.3 A $\dot{\rho}_{\rm SFR}$-dependent IMF: integrated galactic IMFs dependent on star formation history?

A $\dot{\rho}_{\rm SFR}$-dependent IMF as the natural outcome of CR-controlled SF initial conditions in galaxies can also naturally yield integrated galactic IMFs (IGIMFs) that depend on the star formation history (SFH) of galaxies. This is because $\dot{\rho}_{\rm SFR}$ can be a strong function of the evolution of a galaxy, especially during its early and presumably gas-rich state even when no mergers are involved. Such an SFH-dependance of the IGIMFs has been considered before as the cause of the well-known mass–metallicity relation of galaxies (Köppen, Weidner & Kroupa 2007).

4.4 CR propagation in dense molecular gas: a dynamic view is needed

Setting $U_{\rm CR} \propto \dot{\rho}_{\rm SFR}$ in CRDRs assumes that CRs can freely penetrate and warm the entire volume of a GMC down to its densest UV-shielded regions. Recent γ-ray observations have directly measured CR energy densities in the nucleus of a nearby galaxy on par with those computed for extreme CRDRs and expected from its SFR density, while indicating only mildly calorimetric conditions for the CR/ISM p–p interactions (Acero et al. 2009). The latter supports an unhindered CR penetration through the molecular clouds. Nevertheless Alfvén waves generated *outside* such clouds by a net flux of CRs in their environments could be effective in keeping low-energy

CRs below a few hundred MeV (those most effective in heating the gas) outside their high-density regions (Skilling & Strong 1976), which in turn would affect their thermal balance, their fragmentation properties and the emergent stellar IMF. Thus the coupled problems of CR transport, magnetic field dynamics and gravoturbulent evolution of non-isothermal dense molecular gas with high degrees of ionization like those expected in compact extreme starbursts such as Arp 220 (e.g. Greve et al. 2009) must be investigated with dedicated magnetohydrodynamics simulations.

4.5 Observational prospects

The detections of γ-ray emission from two nearby galaxies, namely M 82 and the starburst nucleus of NGC 253 (Acciari et al. 2009; Acero et al. 2009), are two very important recent developments in γ-ray astronomy, given that γ-ray emission results from CR proton interactions with the molecular ISM. This allows such observations to directly measure the average CR energy densities in SF environments, and thus sensitive such measurements in ULIRGs such as the nearby ULIRG Arp 220 will be very important in revealing extreme CRDRs in such systems.

On the other hand, direct measurements of the expected top-heavy IMFs in the heavily dust-enshrouded compact starbursts where extreme CRDRs would reside are impossible. However, any cases where the 'end' products, i.e. the stellar populations, of high-$\dot{\rho}_{\rm SFR}$ SF events can be observed and their IMF determined such as the GC and local ultra compact dwarfs (UCDs) allow such direct observational tests. There is indeed strong evidence of CR heating of the dense molecular gas in the GC, setting $T_{\rm kin} > T_{\rm dust}$, and expected strong effects on the local Jeans mass and ambipolar diffusion time-scales (Yusef-Zadeh et al. 2007). Unfortunately, initial assertions about a top-heavy IMF in the GC (e.g. Nayakshin & Sunayev 2005) and the massive Arches cluster near it (Figer et al. 1999; Stolte et al. 2002, 2005) have not been corroborated by later studies (Kim et al. 2006; Espinoza, Selman & Melnick 2009; Löckmann, Baumgardt & Kroupa 2010). On the other hand, some evidence exists for a top-heavy IMF in the nuclear starburst of M 82 (e.g. Rieke et al. 1980, 1993), and a significantly enhanced $U_{\rm CR}$ is certainly there ($\sim$500 × $U_{\rm CR,Gal}$, directly measured via γ-ray observations; Acciari et al. 2009) to achieve this via a CR-boosted $M^{(*)}_{\rm ch}$ IMF mass scale. Indeed for such $U_{\rm CR}$ values, setting $M^{(*)}_{\rm ch} \sim M_{\rm J}(10^5\,{\rm cm}^{-3})$ yields $M^{(*)}_{\rm ch}({\rm M\,82}) > 2\,{\rm M}_{\odot}$ (Fig. 4). However, the GC does offer an example of regions with locally boosted $U_{\rm CR}$ values that do not necessarily correspond to top-heavy IMFs in their vicinity, possibly because such boosts are too short and transient to systematically bias the local emergent IMF.

Stronger evidence for top-heavy IMFs exists in UCDs, small stellar systems with $r_{\rm e} \sim 10$–30 pc (half-light radius) where $\sim 10^6$–$10^7\,{\rm M}_{\odot}$ of gas have been converted into stars at $\langle {\rm SFR}\rangle \sim 10$–$100\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ (see Dabringhausen, Kroupa & Baumgardt 2009, and references therein). Unlike the GC where IMF studies are hindered by high extinction and tidal disruption of clusters, and where any high-$\dot{\rho}_{\rm SFR}$ SF episodes may have been short-lived (and thus could not significantly bias its average IMF towards a top-heavy one), the IMFs in UCDs are much more amenable to systematic studies, while their SF episodes have had $\langle \dot{\rho}_{\rm SFR}({\rm UCDs})\rangle \gtrsim \langle \dot{\rho}_{\rm SFR}({\rm ULIRGs})\rangle$! They are thus ideal targets for studying the IMF resulting from completed high-$\dot{\rho}_{\rm SFR}$ SF events.

The next best thing besides studies of the IMF itself is studies of the ISM in CRDRs from which the IMF emerges, especially those in compact extreme starbursts where $\dot{\rho}_{\rm SFR}$ is very high (e.g. ULIRGs) versus systems with more distributed SF and much lower $\dot{\rho}_{\rm SFR}$ values. The unique observational signatures of the very warm dense gas with high ionization fractions expected in extreme CRDRs have already been discussed in some detail by Papadopoulos (2010), and the interested reader is referred to this work. In summary, in the era of *Herschel* and the upcoming era of ALMA the sole main obstacle is the degeneracy of extreme CRDR diagnostic with that of X-ray dominated regions (XDRs) induced in the ISM by an X-ray luminous active galactic nucleus (AGN). Indeed, unless an X-ray luminous AGN can be excluded by other independent means (e.g. deep X-ray observations), it can be difficult to tell extreme CRDRs and XRDs apart in a simple fashion as even exotic high excitation species such as $\rm OH^+$ and $\rm H_2O^+$, recently detected by *Herschel* in the archetypal ULIRG/quasi-stellar object (QSO) Mrk 231 and attributed to XDRs (van der Werf et al. 2010) could be partly due to CRDRs. In recent work, Meijerink et al. (2011) provide a detailed discussion of diagnostics lines in extreme CRDRs versus XDRs and the key observations that can separate them.

Finally, it is worth noting that X-rays and XDRs will have similar effects as CRs on the Jeans mass and the IMF of UV-shielded dense gas regions as both can volumetrically warm such regions to high temperatures. This was pointed out recently by Bradford et al. (2009) for the ISM of a distant QSO, and constitutes an omitted aspect of AGN feedback on SF. This has been studied recently and shown to lead to a top-heavy IMF (Hocuk & Spaans 2010). XDRs besides elevating $T_{\rm k}$(min) to much higher values than in the Galaxy also yield $T_{\rm kin} \gg T_{\rm dust}$ (and thus they can also 'erase' the EOS inflection point), though unlike CRDRs their influence on the ISM is necessarily limited by the $\sim 1/R^2_{\rm AGN}$ geometric factor ($R_{\rm AGN}$ the distance of the irradiated gas from the AGN).

5 CONCLUSIONS

We have conducted new, detailed calculations on the thermal balance of UV-shielded dense gas in CRDRs, the ISM phase where the initial conditions of SF are set in galaxies, in order to examine in detail the effects of extreme CRDRs on the mass scale of young stars and the IMF recently suggested by Papadopoulos (2010). Our results can be summarized as follows.

(1) We confirm the high temperatures of dense gas cores in the extreme CRDRs expected in ULIRGs and all systems with large SFR densities ($\dot{\rho}_{\rm SFR}$), albeit at lower levels than the original study.

(2) These CR-induced higher gas temperatures will lead to $\sim$10 times larger Jeans masses across the entire density range typical in such regions, and thus higher characteristic mass of young stars in the ISM of galaxies with high $\dot{\rho}_{\rm SFR}$.

(3) The CRs, by decoupling the thermal state of the gas from that of the dust in CRDRs, keep $T_{\rm k} \gg T_{\rm dust}$ for all densities typical of molecular clouds. This effectively 'erases' the so-called inflection point of the effective EOS, especially in extreme CRDRs, inevitably altering the fragmentation properties of the gas. This effect, along with the expected much higher gas ionization fractions, necessitates a search for a new EOS, appropriate for CRDRs.

(4) These new CR-induced ISM conditions provide a new paradigm for all high-density star formation in the Universe, with CRs as the key SF feedback mechanism, operating unhindered by extinction even in the most dust-enshrouded starbursts.

(5) The resulting $\dot{\rho}_{\rm SFR}$-dependent IMF, yields (i) a natural bimodal behaviour for merger-driven/starburst versus disc/regular-SF galaxies and (ii) IGIMFs that depend on their SFH, both with important consequences in galaxy formation and evolution.

(6) IMF studies of stellar systems formed under extremely high $\langle\dot{\rho}_{\rm SFR}\rangle$ values such as UCDs, and molecular line observations of the extreme CRDRs in nearby ULIRGs can provide the full picture of CRDR properties and their effects on the IMF. Regarding the latter, the now space-borne *Herschel Space Observatory*, and the upcoming ALMA hold particular promise.

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APPENDIX A: THE COOLING AND HEATING FUNCTIONS FOR UV-SHIELDED CORES

The CR heating rate used in this work is

$$\Gamma_{\rm CR} = 1.95\times10^{-28} n_{\rm H} \left(\frac{\zeta_{\rm CR}}{1.3\times10^{-17}\,{\rm s}^{-1}}\right)\ {\rm erg\,cm^{-3}\,s^{-1}}, \qquad ({\rm A1})$$

(Wolfire et al. 1995) where $\zeta_{\rm CR} \propto U_{\rm CR}$ being the CR ionization rate (in s^{-1}), with a adopted Galactic value of $\zeta_{\rm CR} = 5\times10^{-17}\,{\rm s}^{-1}$ (corresponding to $U_{\rm CR} = U_{\rm CR,Gal}$), and $n_{\rm H} = 2n({\rm H_2})$ for fully molecular gas cores. For an optically thin O I line, the cooling is $\Lambda_{\rm O\,I\,63} = \chi_{\rm O} n_{\rm H} C_{\rm lu} E_{\rm ul}$, which becomes

$$\Lambda_{\rm O\,I\,63} = 3.14\times10^{-14} \chi_{\rm O} n_{\rm H} C_{\rm ul} \left(\frac{g_{\rm u}}{g_{\rm l}}\right) \exp\left(-227.72/T_{\rm k}\right) {\rm erg}\,, \qquad ({\rm A2})$$

where $g_{\rm u} = 3$ and $g_{\rm l} = 5$ and $\chi_{\rm O} = [{\rm O/H}]$ being the abundance of oxygen not locked on to CO ($\chi_{\rm O} \sim 4.89\times10^{-4}$). The collisional de-excitation coefficient is given by

$$C_{\rm ul} = n_{\rm H} 10^{0.32\log T_{\rm k} - 10.52} = 3.02 \times 10^{-11} n_{\rm H} T_{\rm k}^{0.32}\,{\rm cm^{-3}\,s^{-1}}, \qquad {\rm (A3)}$$

(Liseau et al. 1999). Thus finally equation (A2) becomes

$$\Lambda_{\rm O\,I\,63} = 2.78 \times 10^{-28} n_{\rm H}^2 T_{\rm g}^{0.32} \exp\left(-227.72/T_{\rm k}\right) {\rm erg\,cm^{-3}\,s^{-1}}. \qquad {\rm (A4)}$$

At lower densities ($n_{\rm H} < 10^5\,{\rm cm^{-3}}$) and strong CR fluxes, a small fraction of carbon remains in the form of C II, acting as a coolant with

$$\Lambda_{\rm C\,II} = 1.975 \times 10^{-23} n_{\rm H}^2 \chi_{\rm C\,II} \exp\left(-92.2/T_{\rm k}\right) {\rm erg\,cm^{-3}\,s^{-1}}, \qquad {\rm (A5)}$$

computed in a similar fashion as the O I (63 μm) line cooling, and for a fully transparent medium. Gas–grain accommodation can heat or cool the gas depending on the difference between their temperatures (Burke & Hollenbach 1983). It can be expressed as

$$\Gamma_{\rm acc} = 4.0 \times 10^{-12} \alpha n_{\rm H} n_{\rm d} \sigma_{\rm g} \sqrt{T_{\rm k}}\left(T_{\rm k} - T_{\rm dust}\right), \qquad {\rm (A6)}$$

where $n_{\rm g}$ is the number density of dust grains and $\sigma_{\rm g}$ is the grain cross-section (cm^{-2}). If the gas-to-dust ratio is 100, the dust mass density is $\rho_{\rm d} = 3.5\,{\rm g\,cm^{-3}}$, and a dust radius of $a = 0.1$ μm then

$$n_{\rm d} = 2.2 \times 10^{-2} \times \mu_{\rm H} n_{\rm H}/(4/3\pi\rho_{\rm d} a^3) = 7.88 \times 10^{-12} n_{\rm H}. \qquad {\rm (A7)}$$

For the accommodation factor α, we follow the treatment by Groenewegen (1994) where

$$\alpha = 0.35 \exp\left(-\sqrt{\frac{T_{\rm dust} + T_{\rm k}}{500}}\right), \qquad {\rm (A8)}$$

which we set to the maximum value $\alpha = 0.35$ (i.e. maximum gas cooling from gas–dust interaction). Thus the main cooling term (for the ISM conditions explored here) due to the gas–dust interaction in equation (A6) becomes

$$\Lambda_{\rm gd} = 3.47 \times 10^{-33} n_{\rm H}^2 \sqrt{T_{\rm k}}\left(T_{\rm k} - T_{\rm dust}\right) {\rm erg\,cm^{-3}\,s^{-1}}. \qquad {\rm (A9)}$$

Finally based on our UCL-PDR code outputs we parametrize the cooling due to the CO rotational transitions as

$$\Lambda_{\rm CO} = 4.4 \times 10^{-24} \left(\frac{n_{\rm H}}{10^4\,{\rm cm^{-3}}}\right)^{3/2} \left(\frac{T_{\rm k}}{10\,{\rm K}}\right)^{2} \left(\frac{\chi_{\rm CO}}{\chi_{\rm [C]}}\right) {\rm erg\,cm^{-3}\,s^{-1}}, \qquad {\rm (A10)}$$

where we set $\chi_{\rm CO}/\chi_{\rm [C]} = (0.97, 0.98, 0.99, 1.0)$ for densities of 5×10^3, 10^4, 10^5, $10^6\,{\rm cm^{-3}}$, respectively (with the value of = 1 corresponding to all carbon locked on to CO).

Solutions of equation (2) in the main text for densities spanning the range present in star-forming H_2 clouds in galaxies, and $U_{\rm CR} = (0.2, 1.0, 10, 10^2, 10^3, 10^4) \times U_{\rm CR,Gal}$ are then obtained numerically and are shown in Fig. 1.

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