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A COSMIC-RAY-DOMINATED INTERSTELLAR MEDIUM IN ULTRA LUMINOUS INFRARED GALAXIES: NEW INITIAL CONDITIONS FOR STAR FORMATION

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ABSTRACT

The high-density star formation typical of the merger/starburst events that power the large IR luminosities of ultraluminous infrared galaxies (ULIRGs) ($L_{\rm IR}(8\text{–}1000\ \mu{\rm m}) \gtrsim 10^{12}\ L_\odot$) throughout the universe results in extraordinarily high cosmic-ray (CR) energy densities of $U_{\rm CR} \sim$ few $\times (10^3\text{–}10^4)\ U_{\rm CR,Gal}$ permeating their interstellar medium, a direct consequence of the large supernova remnant number densities in such systems. Unlike far-UV photons emanating from numerous star-forming (SF) sites, these large CR energy densities in ULIRGs will volumetrically heat and raise the ionization fraction of dense ($n > 10^4$ cm^{-3}) UV-shielded gas cores throughout their compact SF volumes. Such conditions can turn most of the large molecular gas masses found in such systems and their high redshift counterparts ($\sim 10^9\text{–}10^{10}\ M_\odot$) into giant CR-dominated regions (CRDRs) rather than ensembles of photon-dominated regions (PDRs) which dominate in less IR-luminous systems where star formation and molecular gas distributions are much more extended. The molecular gas in CRDRs will have a minimum temperature of $T_{\rm kin} \sim$ (80–160) K, and very high ionization fractions of $x(e) > 10^{-6}$ throughout its UV-shielded dense core, which in turn will *fundamentally alter the initial conditions for star formation in such systems*. Observational tests of CRDRs can be provided by high-J CO and ^{13}CO lines or multi-J transitions of any heavy rotor molecules (e.g., HCN) and their isotopologs. Chemical signatures of very high ionization fractions in dense UV-shielded gas such as low [DCO^+]/[HCO^+] and high [HCO^+]/[CO] abundance ratios would be good probes of CRDRs in extreme starbursts. These tests, along with direct measurements of the high CO line brightness temperatures expected over the areas of compact dense gas disks found in ULIRGs, will soon be feasible as sub-arcsecond interferometric imaging capabilities and sensitivity at millimeter/submillimeter wavelengths improve in the era of ALMA.

Key words: cosmic rays – dust, extinction – galaxies: starburst – galaxies: star formation – ISM: molecules – ISM: supernova remnants

Online-only material: color figure

1. INTRODUCTION

For some time, cosmic rays (CRs) have been established as the main regulators of the temperature, ionization, and chemical state of dense gas cores lying deep inside the far-UV-shielded regions of molecular clouds (e.g., Goldsmith & Langer 1978; Goldsmith 2001; Lequeux 2004 and references therein). The association of CRs with O, B star clusters and supernova remnants (SNRs) where they are accelerated (in massive-star winds and supernova (SN) shocks) has been recently demonstrated for the Galaxy (Binns et al. 2008) and even shown for individual SNRs (Acciari et al. 2009a) and star-forming (SF) regions (Abdo et al. 2010), while the synchrotron emission of CR electrons is a well-established marker of SF regions (e.g., Condon et al. 1990, 1991). The recent detections of γ-rays (the product of inelastic collisions between CR-protons and hydrogen nuclei in the interstellar medium (ISM)) from the starburst nuclei of M 82 and NGC 253 solidified the connection of CR energy density to SNRs and star formation activity in galaxies (Acciari et al. 2009b; Acero et al. 2009). CRs rather than far-UV photons have even been advocated as the dominant heating mechanism of molecular gas in galaxies irrespective of their star formation activity (Suchkov et al. 1993 and references therein). These early proposals, however, faced two distinct problems: (1) ensembles of standard photon-dominated regions (PDRs) accounted well for the global molecular and atomic line emission from quiescent spirals such as the Milky Way (Fixsen et al. 1999; Mochizuki & Nakagawa 2000) as well as starbursts (e.g., Wolfire et al. 1990; Mao et al. 2000) and (2) a tight correlation between CO line brightness and non-thermal radio continuum used as evidence for CR heating of molecular gas can also be attributed to the well-known far-IR/radio correlation. The latter is established by star formation powering both the far-IR dust continuum and the non-thermal radio emission in galaxies, with far-UV photons from SF sites heating the dust (and thus the gas via photoelectric heating) and reprocessed into the far-IR continuum (e.g., Condon & Yin 1990; Condon 1992). The tight far-IR/radio correlation and the close association of O, B stars and SNRs (the sites of both far-UV photons and CR acceleration) down to individual CO-luminous giant molecular clouds (GMCs) can then easily account for the observed (CO intensity)/(radio continuum) correlation without CR heating of CO-bright clouds as an underlying cause (i.e., the far-IR/radio becomes a CO/radio correlation as CO luminosity is a good proxy for far-IR luminosity).

It was the recent capability for sensitive observations of high-excitation high-J transitions of CO and ^{13}CO that “broke” the aforementioned degeneracies and definitively demonstrated the presence of CR-heated molecular gas in the starburst nucleus of the otherwise quiescent spiral galaxy NGC 253 (Bradford et al. 2003; Hailey-Dunsheath et al. 2008), while strong evidence suggests that this is also the case for the dense molecular cloud in Sgr B2 at the Galactic center (Yusef-Zadeh et al. 2007). Nevertheless, these amount to only $\sim$0.1%–1% of the total molecular gas found in typical spirals and thus do not change the paradigm of far-UV photons as the main heating agent of molecular gas in IR-luminous galaxies. It must be noted that irrespective of whether CRs heat most of the molecular gas in galaxies or not, they remain the ultimate regulator of its temperature and ionization fraction minima, both reached in its densest, UV-shielded phase deep inside molecular clouds.

2. THE CR ENERGY DENSITY IN ULIRGs: A CR-DOMINATED ISM

It is the star formation rate (SFR) *density* rather than the total SFR that determines the CR energy density U_{CR} (eV cm^{-3}) in the ambient ISM of a galaxy. Indicatively, for the 100 pc starburst nucleus of NGC 253, the latter is $\sim 2 \times 10^3$ times higher than the Galactic value ($\sim$0.5 eV cm^{-3}) even though their global SFRs are similar (Acero et al. 2009). In the central 500 pc of the nearby starburst M 82, it is $U_{CR} \sim 500 \times U_{CR,Gal}$ (Suchkov et al. 1993; Acciari et al. 2009b) while its globally averaged CR energy density remains similar to that of the Galaxy. Such high values of U_{CR} can be easily attained and surpassed over the entire volume of the substantial reservoirs of molecular gas ($\sim(10^9$–$10^{10})\ M_\odot$) in ultraluminous infrared galaxies (ULIRGs) and their high redshift counterparts. Indeed, the large IR luminosities of these extreme starbursts (L_{IR} (8–1000 μm) $\gtrsim 10^{12}\ L_\odot$) emanate from very small volumes with typical IR brightnesses of

$$\sigma_{IR}(\text{ULIRGs}) = (10^{12}\text{–}10^{14})\,\frac{L_\odot}{\text{kpc}^2}, \qquad (1)$$

and with most such systems strongly clustering around $\sigma_{IR} \sim 10^{13}\ L_\odot\ \text{kpc}^{-2}$ (Thompson et al. 2005). This latter value could be indicating radiation-pressure-regulated maximal starbursts (Thompson et al. 2005; Thompson 2009), where an Eddington limit from O, B star clusters sets a maximum gas accretion rate onto SF sites deep inside molecular clouds via photon pressure on its concomitant dust (see also Scoville 2004 for an earlier and simple exposition). Interestingly, a similar threshold value for σ_{IR} can also be recovered with CRs instead of photons setting the Eddington limit (Socrates et al. 2008) as CRs are much more highly coupled to the ISM than photons. Either way the high σ_{IR} values typical in ULIRGs seem to be the result of extreme starbursts occurring in very compact regions, while for less IR-luminous systems ($L_{IR} \lesssim 10^{11}\ L_\odot$), which typically have more extended star formation: $\sigma_{IR} = (10^{10}$–$10^{11})\ L_\odot\ \text{kpc}^{-2}$ (Lehnert & Heckman 1996). For nearby ULIRGs, this compactness of their molecular gas reservoirs (and thus of their SF volumes) has been demonstrated using millimeter and (recently) submillimeter interferometric imaging of their CO line and dust continuum that found gaseous disks with D $\sim$(100–300) pc (e.g., Downes & Solomon 1998; Sakamoto et al. 2008; Matsushita et al. 2009). Moreover, even when such systems initially seem to have larger dimensions, higher-resolution millimeter/submillimeter interferometry frequently reveals them as mergers of such compact nuclei, each containing the molecular gas of a gas-rich progenitor with $M(H_2) \sim (10^9$–$10^{10})\ M_\odot$ (Evans et al. 2002; Sakamoto et al. 2008).

Recently, σ_{IR} values similar to those typical for local ULIRGs have also been found for a submillimeter-selected galaxy at $z \sim 2.3$, where a unique combination of high-resolution submillimeter imaging and a strong magnification by gravitational lensing made the resolution of the SF area of this distant ULIRG possible at linear scales of $\sim$100 pc (Swinbank et al. 2010). Finally, while the level of the contribution of an active galactic nucleus (AGN) to the tremendous σ_{IR} values of such compact regions remains a matter of debate (e.g., Downes & Eckart 2007), it can be safely assumed that they are good order-of-magnitude "calorimeters" of dust-obscured SFR (e.g., in the archetypal QSO/starburst system Mrk 231: $L_{IR} = 2/3(\text{starburst}) + 1\ 3(\text{AGN})$; Downes & Solomon 1998). This is further supported by the large number of radio SNRs recently found within the gaseous disks of ULIRGs using very long baseline interferometry imaging (Sakamoto et al. 2008 and references therein; Pérez-Torres et al. 2009), while similar AGN contributions to total IR luminosities are also recovered for dusty starbursts at high redshifts (Pope et al. 2008; Murphy et al. 2009).

The IR-luminosity surface density and the SN rate surface density can then be related using the well-established IR/radio correlation

$$\frac{[\nu(\text{GHz})L_\nu]}{L_{IR}} = \mu(\nu)\,10^{-6} \qquad (2)$$

(Yun et al. 2001 and references therein). This relates the power νL_ν of the non-thermal radio continuum to the IR luminosity (and holds over 5 orders of magnitude with a dispersion $\lesssim$80%), with the SFR considered to be the ultimate scaling factor for both IR and non-thermal radio luminosities (see Thompson et al. 2006 for the latest theoretical background). To obtain a working value for $\mu(\nu)$, we follow Yun et al. (2001) and use their value for the far-IR/radio correlation at $\nu = 1.4$ GHz: $(\nu L_\nu)/L_{FIR} = 2.66 \times 10^{-4} \times 10^{-q}$, where $q = 2.35$ (as defined by Helou et al. 1985). For $\langle L_{IR}(8\text{–}1000\ \mu\text{m})/L_{FIR}(42\text{–}120\ \mu\text{m})\rangle = 1.3$ (Yun et al. 2001), the coefficient in Equation (2) becomes $\mu(\nu) = 1.54$ and is adopted for this study (with an inherent uncertainty of a factor of $\sim$2 due to a varying L_{FIR}/L_{IR} in IR-luminous galaxies). On the other hand, the non-thermal radio power depends on the SN rate f_{SN} as

$$\frac{L_\nu}{10^{22}\ \text{W Hz}^{-1}} = 13\ [\nu(\text{GHz})]^{-\alpha} f_{SN}(\text{yr}^{-1}), \qquad (3)$$

(Condon 1992). Combining Equations (2) and (3) and assuming full concomitance of IR and non-thermal radio emission over the SF regions yields the SN rate surface density

$$\frac{\dot{\Sigma}_{SN}}{\text{yr}^{-1}\ \text{kpc}^{-2}} = 2.95\,\mu(\nu)\left(\frac{\sigma_{IR}}{10^{12}\ L_\odot\ \text{kpc}^{-2}}\right)[\nu(\text{GHz})]^{\alpha-1}. \quad (4)$$

Following Suchkov et al. (1993), the CR energy densities in ULIRGs scale with respect to that of the Galaxy as

$$\frac{U_{CR}}{U_{CR,Gal}} \sim \frac{\dot{\Sigma}_{SN}}{\dot{\Sigma}_{SN,Gal}} \times \left(\frac{V_{diff}}{V_{wind}}\right), \qquad (5)$$

where $\dot{\Sigma}_{SN,Gal} = 3.85 \times 10^{-5}\ \text{yr}^{-1}\ \text{kpc}^{-2}$ (McKee & Williams 1997) and V_{diff} is the diffusion velocity at which CRs escape from quiescent disks like the Milky Way while V_{wind} is the velocity of an SF-induced wind at which CRs are advected out of the SF regions in starbursts. Typically, $V_{diff} \sim 10$ km s^{-1} while the maximum velocity of SF-driven galactic winds is $V_{wind,max} \sim (2\text{–}3) \times 10^3$ km s^{-1} (Suchkov et al. 1993; Veilleux et al. 2005). Such starburst-induced high wind velocities are deduced for M 82 (Seaquist et al. 1985) though usually $V_{wind} \sim$ (500–1000) km s^{-1}. From Equations (4) and (5), after setting $V_{wind,max} = 3000$ km s^{-1}, and $\mu(\nu) \sim 1.54$, $\alpha = 0.8$ (for $\nu = 1.4$ GHz), Equation (1) yields a CR energy density in compact starbursts (CSBs) of

$$\frac{U_{CR,CSB}}{U_{CR,Gal}} \sim 4 \times (10^2\text{–}10^4). \qquad (6)$$

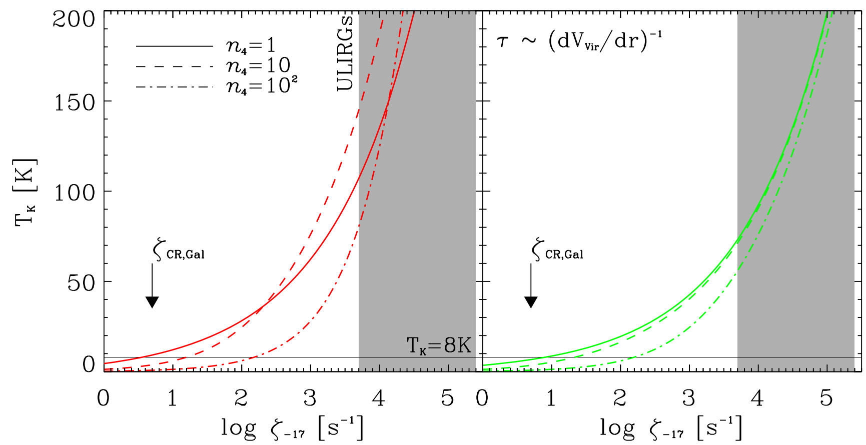

Figure 1. Temperatures of UV-shielded gas in CRDRs of compact extreme starbursts in ULIRGs (marked by the shaded area) for cores with densities $n(H_2) = (10^4, 10^5, 10^6)$ cm^{-3} (solid, dashed, and dash-dotted lines, respectively) and near-thermal motions (left), or dictated by gas self-gravity (right) that yield larger than thermal linewidths and stronger line cooling (see Section 2.1). The horizontal line marks the typical temperature of this gas phase in the Galaxy. The arrow marks the adopted Galactic CR ionization rate of $\zeta_{\rm CR,Gal} = 5 \times 10^{-17}$ s^{-1}.

(A color version of this figure is available in the online journal.)

For ULIRGs as the template CSBs $\sigma_{\rm IR} = 10^{13}\ L_\odot$ kpc^{-2}, yielding $U_{\rm CR,CSB} \sim 4 \times 10^3 U_{\rm CR,Gal}$. The latter amounts to a tremendous boost of CR energy density, similar to that found recently for a single molecular cloud in the nucleus of NGC 253 (Acero et al. 2009), and is capable of turning the massive and dense molecular clouds of ULIRGs into CR-dominated regions (CRDRs) in terms of the dominant heating mechanism. For the extreme starbursts in ULIRGs and their high redshift counterparts, these high $\sigma_{\rm IR}$ and correspondingly high $U_{\rm CR}$ values can involve $\sim(10^9\text{–}10^{10})\ M_\odot$ of molecular gas mass fueling galaxy-wide SF episodes.

2.1. *CRDRs in ULIRGs: A New Temperature Minimum for UV-shielded Gas*

For the UV-shielded, and mostly subsonic, dense gas cores deep inside molecular clouds, the heating rate is given by

$$\Gamma_{\rm CR} \sim 1.5 \times 10^{-24} \left(\frac{\zeta_{\rm CR}}{10^{-17}\,{\rm s}^{-1}}\right)\left(\frac{n({\rm H_2})}{10^4\,{\rm cm}^{-3}}\right)\ {\rm erg\,cm^{-3}\,s^{-1}}, \tag{7}$$

where $\zeta_{\rm CR}({\rm s}^{-1}) \propto U_{\rm CR}$ is the CR ionization rate per H_2 molecule. The gas cooling via gas-dust interaction can be expressed as

$$\Lambda_{\rm g-d} \sim 10^{-25} \left(\frac{n({\rm H_2})}{10^4\,{\rm cm}^{-3}}\right)^2 T_{\rm k}^{1/2}\,(T_{\rm k} - T_{\rm dust})\ {\rm erg\,cm^{-3}\,s^{-1}} \tag{8}$$

(see Tielens 2005 for derivation of both expressions). The most important line cooling of this gas phase is through rotational lines of CO and a few other molecular species whose rotational ladder energy levels reach down to $E_{\rm ul}/k_{\rm B} \sim (5\text{–}10)$ K. Following the detailed study of Goldsmith (2001), we parameterize the molecular line cooling as

$$\Lambda_{\rm line} \sim 6 \times 10^{-24} \left[\frac{n({\rm H_2})}{10^4\,{\rm cm}^{-3}}\right]^{1/2} \left(\frac{T_{\rm k}}{10\,{\rm K}}\right)^{\beta}\ {\rm erg\,cm^{-3}\,s^{-1}}. \tag{9}$$

The density dependence was extracted from a fit of the parameter α in Table 2 of Goldsmith (2001), which reproduces the values of the $\Lambda_{\rm line}$ to within $\lesssim$20% for $n(H_2) = (10^4\text{–}10^6)$ cm^{-3}, which spans the density range of dense cores within GMCs. For that density range $\beta \sim 3$.

The resulting gas temperature for the CR-heated gas can then be estimated from the equation of thermal balance

$$\Gamma_{\rm CR} = \Lambda_{\rm line} + \Lambda_{\rm g-d}. \tag{10}$$

Setting the dust temperature to $T_{\rm dust} = 0$ K will yield a minimum $T_{\rm k}$ value while also allowing a simple analytic solution of Equation (10). Substituting the expressions from Equations (7)–(9) into the latter yields

$$T^3_{\rm k,10} + 0.526 n_4^{3/2} T^{3/2}_{\rm k,10} = 0.25 n_4^{1/2} \zeta_{-17}, \tag{11}$$

where $T_{\rm k,10} = T_{\rm k}/(10\ {\rm K})$, $n_4 = n({\rm H_2})/(10^4\ {\rm cm}^{-3})$ and $\zeta_{-17} = \zeta_{\rm CR}/(10^{-17}\ {\rm s}^{-1})$. An exact solution of the latter is then

$$T_{\rm k,10} = 0.630\left[\left(n_4^{1/2}\zeta_{-17} + 0.276676 n_4^3\right)^{1/2} - 0.526 n_4^{3/2}\right]^{2/3}. \tag{12}$$

For $\zeta_{\rm CR,Gal} = 5 \times 10^{-17}$ s^{-1} for the Galaxy (e.g., van der Tak & van Dishoeck 2000) and $n(H_2) = 10^4$ cm^{-3}, the latter yields $T_{\rm k} \sim 9$ K, which is typical for UV-shielded gas immersed in Galactic CR energy density (e.g., Goldsmith 2001), and is deduced by numerous observations in the Galaxy (e.g., Pineda & Bensch 2007; Bergin & Tafalla 2007). For $\zeta_{\rm CR,CSB} = (1\text{–}4) \times 10^3 \zeta_{\rm CR,Gal}$ expected for the ISM of extreme starbursts and $n(H_2) = (10^4\text{–}10^6)$ cm^{-3} (typical densities for dense cores in the Galaxy, e.g., Bergin & Tafalla 2007), Equation (12) yields $T_{\rm k} \sim (80\text{–}240)$ K, as *the minimum possible temperature for the molecular gas in compact extreme starbursts* (see Figure 1). Turbulent gas heating (e.g., Pan & Padoan 2009) that may "seep" down the molecular cloud hierarchical structures to the dense gas cores (although because they are typically subsonic, such heating is expected to be negligible), any sort of mechanical heating of the dense gas in ULIRGs (Baan et al. 2010) or warmer dust because of IR light "leaking" deep inside molecular clouds can only raise this temperature range.

The gas cores deep inside the CR-heated regions of molecular clouds in the Galaxy and especially the highest density ones $(\sim(10^5\text{–}10^6)$ cm$^{-3})$ are typically dominated by near-thermal motions (e.g., Bergin & Tafalla 2007). However, the often large turbulent linewidths found in the dense gas disks of nearby ULIRGs (Downes & Solomon 1998; Sakamoto et al. 2008; Matsushita et al. 2009) could in principle affect even dense gas core kinematics and thus their line cooling function. Following Goldsmith (2001) that any such macroscopic motions are driven mostly by self-gravity, a new effective line cooling function would be

$$\Lambda^{(\mathrm{eff})}_{\mathrm{line}} = \Lambda_{\mathrm{line}} \times \left(\frac{n(\mathrm{H_2})}{10^3\ \mathrm{cm^{-3}}}\right)^{1/2}, \tag{13}$$

which roughly quantifies the effect of increased transparency (and thus cooling power) of molecular line photons. An optical depth dependence of $\tau \propto (dV/dR)^{-1}$ is adopted, where $(dV/dR)_{\mathrm{VIR}} = \left[n(\mathrm{H_2})/(10^3\,\mathrm{cm^{-3}})\right]^{1/2}$ km s^{-1} pc^{-1} is the velocity gradient of macroscopic motions for self-gravitating gas. The equation of thermal balance and its solution then become

$$T^3_{\mathrm{k},10} + 0.166 n_4 T^{3/2}_{\mathrm{k},10} = 0.0789\zeta_{-17}, \tag{14}$$

and

$$T_{\mathrm{k},10} = 0.630\left[\left(0.02766 n_4^2 + 0.3156\zeta_{-17}\right)^{1/2} - 0.1663 n_4\right]^{2/3}, \tag{15}$$

(where we set again $T_{\mathrm{dust}} = 0$ K). For $\zeta_{\mathrm{CR}} \sim (1\text{–}4) \times 10^3 \zeta_{\mathrm{CR,Gal}}$, the new thermal balance equation yields $T_{\mathrm{k}}(\mathrm{min}) \sim (55\text{–}115)$ K for the molecular gas in such environments while for more extreme CSBs with $\zeta_{\mathrm{CR}} \sim 10^4 \zeta_{\mathrm{CR,Gal}}$ it is $T_{\mathrm{k}}(\mathrm{min}) \sim (145\text{–}160)$ K. In all cases, the minimum temperatures in CRDRs remain significantly higher than the minimum $T_{\mathrm{k}} \sim (8\text{–}10)$ K which is attained in the dark UV-shielded cores in the Galaxy (see Figure 1) where the initial conditions of star formation are set (Bergin & Tafalla 2007).

It must be noted that such high CR energy densities may also affect molecular gas chemistry, and thus the abundance of coolants such as CO. Hence, better temperature estimates of the UV-shielded dense gas cores in CRDRs can only be provided by self-consistent solutions of their thermal *and* chemical states. Moreover, activation of other cooling lines such as O I at 63 μm ($\Delta E_{\mathrm{ul}}/k_{\mathrm{B}} \sim 228$ K) when temperatures rise significantly above 100 K in dense gas ($n(\mathrm{H_2}) \gtrsim 10^5$ cm^{-3}) can cap the rise of $T_{\mathrm{k}}(\mathrm{min}) = F(\zeta_{\mathrm{CR}})$ in CRDRs to ~150 K (W.-F. Thi 2010, private communication). On the other hand, gas temperatures can be even higher than the simple estimates provided by Equation (10) because residual turbulent motion dissipation (and thus heating) remains possible in the dense gas reservoirs of ULIRGs, as they may resemble the tidally stirred dense gas in the Galactic center where turbulent heating remains important even at high densities (e.g., Stark et al. 1989; Rodríguez-Fernández et al. 2001; Güsten & Philipp 2004).

2.2. The Ionization Fraction of Dense Gas in ULIRGs

The large CR energy densities, besides significantly raising the minimum possible temperature of molecular gas in the CSBs powering ULIRGs and their high redshift counterparts, they will also dramatically raise the minimum ionization fraction. Following the treatment by McKee (1989), in UV-shielded environments with negligible photoionization and CRs as the sole cause of ISM ionization, the ionization fraction $x(e) = n_{\mathrm{e}}/n(\mathrm{H}) = n_{\mathrm{e}}/2n(\mathrm{H_2})$ is given by

$$x(e) = 2 \times 10^{-7} \mathrm{r}_{\mathrm{gd}}^{-1} \left(\frac{n_{\mathrm{ch}}}{2n(\mathrm{H_2})}\right)^{1/2} \times \left[\left(1 + \frac{n_{\mathrm{ch}}}{8n(\mathrm{H_2})}\right)^{1/2} + \left(\frac{n_{\mathrm{ch}}}{8n(\mathrm{H_2})}\right)^{1/2}\right], \tag{16}$$

where $n_{\mathrm{ch}} \sim 500\ (\mathrm{r}^2_{\mathrm{gd}}\zeta_{-17})\,\mathrm{cm^{-3}}$ is a characteristic density encapsulating the effect of CRs and ambient metallicity on the ionization balance (r_{gd} is the normalized gas/dust ratio $\mathrm{r}_{\mathrm{gd}} = [(\mathrm{G/D})/100]$ with G/D(gas-to-dust mass) = 100 assumed for solar metallicities, e.g., Knapp & Kerr 1974; Aannestad & Purcell 1973).

For the Galaxy where $\zeta_{\mathrm{CR,Gal}} = 5 \times 10^{-17}$ s^{-1}, it is $n_{\mathrm{ch}} = 2.5 \times 10^3$ cm^{-3} and for a typical dense core density of $n(\mathrm{H_2}) = 10^5$ cm^{-3}, Equation (16) yields $x(e) \sim 2.4 \times 10^{-8}$, consistent with the typical range in the Galaxy: $5 \times 10^{-9} \lesssim x(e) \lesssim 1.5 \times 10^{-7}$ (e.g., Langer 1985). For the much larger CR ionization rates, $\zeta_{\mathrm{CR,CSB}} = 10^3 \times \zeta_{\mathrm{CR,Gal}}$ expected in the ISM of CSBs: $n_{\mathrm{ch}} = 2.5 \times 10^6$ cm^{-3} and $x(e) \sim 4 \times 10^{-6}$. The latter is 1–2 orders of magnitude larger than the typical range and ~4 times higher than the highest value measured for dense UV-shielded cores anywhere in the Galaxy (Caselli et al. 1998). In the classic photoionization-regulated star formation scenario (McKee 1989), such high ionization fractions will be capable of turning even very dense gas in the UV-shielded/CR-ionized regions of molecular clouds subcritical (i.e., $M_{\mathrm{core}}/M_\Phi < 1$, where $M_\Phi = 0.12\Phi/\mathrm{G}^{1/2}$ and Φ is the magnetic field flux threading the molecular core; Mouschovias & Spitzer 1976), and thus halt their gravitational collapse until a now much slower ambipolar diffusion allows it.

3. IMPORTANT CONSEQUENCES AND SOME KEY OBSERVATIONAL TESTS

The CR-permeated molecular gas in compact extreme starbursts is more than the mere sum of individual SF regions and their localized dense PDRs. The latter would leave most of the dense gas settle to a cold state since for the high gas densities found in ULIRGs, far-UV field intensities will be reduced by factors of ~10^4 over distances of $\lesssim$0.1 pc. On the other hand, by dramatically altering the thermal and ionization state of dense UV-shielded gas cores inside molecular clouds, the large CR energy densities in extreme starbursts significantly *alter the initial conditions for star formation in such systems*. Indeed, it is in the UV-shielded dense gas cores where these initial conditions are set, and the large temperatures expected for these cores throughout CRDRs invalidate the main arguments about an almost constant characteristic mass of young stars in most ISM environments including starbursts (Elmegreen et al. 2008). The latter study did not consider the effects of CRs and as a result found that UV-shielded dense gas remains cold ($T_{\mathrm{k}} \sim 10$ K) even in starbursts.

The much larger ionization fractions that can now be reached deep inside molecular clouds can in principle (1) keep the magnetic field lines strongly "threaded" onto molecular gas at much higher densities and (2) as a result render much of its mass incapable of star formation, at least in the simple photoionization-regulated SF scenario. These effects stem from the now much longer ambipolar diffusion timescale

$$\tau_{\mathrm{AD}} = 3.2 \times 10^7 r_{gd} \left(\frac{n_{\mathrm{ch}}}{2n(H_2)}\right)^{1/2} \times \left[\left(1 + \frac{n_{\mathrm{ch}}}{8n(H_2)}\right)^{1/2} + \left(\frac{n_{\mathrm{ch}}}{8n(H_2)}\right)^{1/2}\right] yr, \tag{17}$$

needed for a CR-ionized dense core with density $n(\mathrm{H_2})$ to lose magnetic flux and collapse (McKee 1989). For the CR ionization rates of $\zeta_{\mathrm{CR}} = \text{few} \times (10^3\text{–}10^4)\zeta_{\mathrm{CR,Gal}}$ expected in CRDRs, it

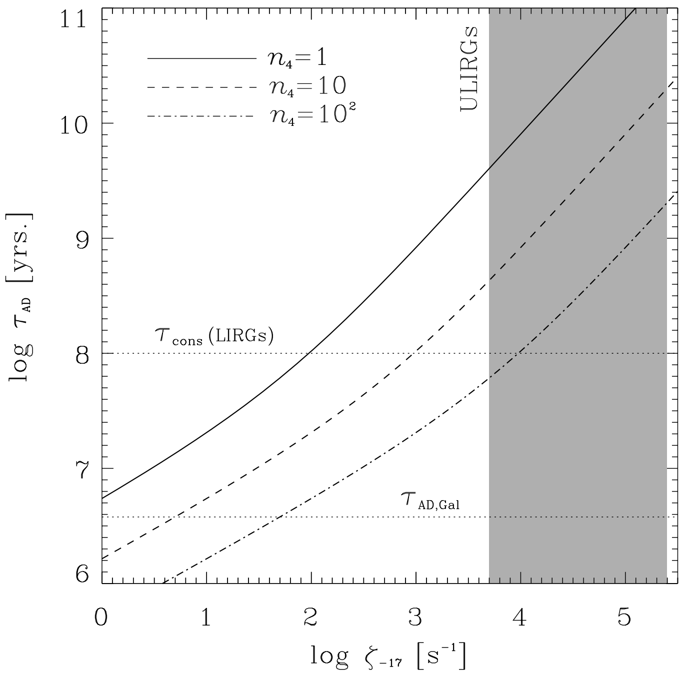

Figure 2. Ambipolar diffusion timescale of UV-shielded gas in CRDRs of compact extreme starbursts in ULIRGs (marked by the shaded area) for cores with densities $n(H_2) = (10^4, 10^5, 10^6)$ cm^{-3} (solid, dashed, and dash-dotted lines, respectively) estimated from Equation (17). The lower horizontal line marked by $\tau_{AD,Gal}$ is the ambipolar diffusion timescale for UV-shielded cores with $n(H_2) = 10^5$ cm^{-3} in the Galaxy for $\zeta_{CR,Gal} = 5 \times 10^{-17}$ s^{-1}, and the higher line marks the gas consumption timescale of the entire molecular gas reservoir of a typical LIRG ($L_{IR} \sim 10^{11}$ $L_\odot$). For the more vigorously star-forming ULIRGs and their HCN-bright dense gas phase, this gas consumption timescale can be an order of magnitude less (Section 3).

would be $n_{ch} = 2.5 \times (10^6\text{–}10^7)$ cm^{-3}, thus for a typical dense core density of $n(H_2) = 10^5$ cm^{-3}, $\tau_{AD} \sim 3 \times (10^8\text{–}10^{10})$ yr (see Figure 2). In photoionization-regulated star formation, this is a *lower* limit on the gas consumption timescale by the latter process, and in CRDRs it is clearly already much longer (by up to two orders of magnitude) than the typical consumption timescale of molecular gas reservoirs of LIRGs (Figure 2). For more vigorously SF ULIRGs and considering only their dense HCN-bright molecular gas phase as the true SF fuel (e.g., Gao & Solomon 2004): $\tau_{cons} = M(n > 10^4$ cm$^{-3})$/SFR $\sim 10^7$ yr, and τ_{AD}/τ_{cons} $(n > 10^4$ cm$^{-3}) \sim 10^2\text{–}10^3$.

This certainly disfavors a simple quasi-static photoionization-regulated SF scenario of B-field lines slowly slipping from stationary dense gas cores which then proceed to star formation. Such a simple picture is expected to be modified anyway by the presence of MHD turbulence which can accelerate the ambipolar diffusion process (Heitsch et al. 2004), especially in the very turbulent molecular gas of ULIRGs. For such systems, the magnetic fields can be strong, in possible equipartition with highly turbulent gas (Thompson et al. 2006), and thus dynamically important and strongly co-evolving with the molecular gas. It may well be that the ability of CRDRs to maintain high ionization fractions in very dense UV-shielded molecular gas, and thus retain a strong coupling of the magnetic fields onto the bulk of its mass in ULIRGs (where $\langle n(H_2)\rangle > 10^4$ cm^{-3}), is what allows a quick establishment of equipartition between magnetic fields and turbulent gas motions in their self-gravitating disks. MHD simulations for gas clouds immersed in the very intense CR energy density backgrounds expected in CRDRs will be a key in addressing these issues and in investigating whether turbulence can still accelerate ambipolar diffusion in molecular clouds of such high ionization fractions and lead back to $\tau_{AD} < \tau_{cons}$ for the dense gas in ULIRGs.

3.1. A New Set of Initial Conditions for Star Formation in ULIRGs

In the high-extinction ISM of compact extreme starbursts, CRDRs make the dramatic change of star formation initial conditions *an imperative of high-density star formation*. The latter occurs irrespective of whether the bulk of the molecular gas in CRDRs of ULIRGs is dominantly heated by CRs or not as the latter will now raise the temperature minimum of pre-stellar UV-shielded dense gas cores throughout their SF volumes by a large factor. The consequences of this new imperative for star formation in extreme starburst environments remain invariant irrespective of whether gravitational instability in turbulent molecular gas (e.g., Klessen 2004; Jappsen et al. 2005; Bonnell et al. 2006) or ambipolar diffusion of magnetic field lines from dissipated dense cores followed by their gravitational collapse (e.g., Mouschovias & Spitzer 1976; McKee 1989) drive star formation in galaxies. In both schemes, the dense UV-shielded cores of molecular clouds are where the initial conditions of star formation are truly set (see Elmegreen 2007; Ballesteros-Paredes & Hartmann 2007 for recent excellent reviews). It must also be noted that this gas phase is different from the PDR-dominated gas around SF sites that dominates the global molecular line and dust continuum spectral energy distributions observed for ULIRGs and often (erroneously) used to set the star formation initial conditions in starbursts (e.g., Klessen et al. 2007).

The effects on the characteristic mass scale of young stars $M^{(*)}_{ch}$ and thus on the stellar initial mass function (IMF; Elmegreen et al. 2008) for the ISM in CRDRs are explored in detail in a forthcoming paper (Papadopoulos et al. 2010). It is nevertheless worth pointing out that the large boost of T_k(min) in CRDRs in an (almost) extinction-free manner across a large range of densities in molecular clouds cannot but have fundamental consequences on $M^{(*)}_{ch}$ and the emergent stellar IMF. Indicatively for a T_k(min) in UV-shielded cores boosted by a factor of 10, the Jeans mass $M_J \propto T_k^{3/2} n(H_2)^{-1/2}$ rises by a factor of ∼32! (over an identical density range) and almost certainly raises $M^{(*)}_{ch}$ and the characteristic mass scale of the stellar IMF. Interestingly, similar effects can also occur in AGN-induced X-ray-dominated regions (XDRs; Schleicher et al. 2010) since X-rays just as CRs (and unlike far-UV photons) can volumetrically heat large columns of molecular gas while experiencing very little extinction. The effect of X-rays on the Jeans mass of dense cores and the IMF has been recently proposed for a powerful distant QSO (Bradford et al. 2009) and it may represent a neglected but important AGN feedback factor on its circumnuclear star formation.

3.2. CRDRs: Observational Tests

The molecular line diagnostics of starburst-induced CRDRs and AGN-originating XDRs can be to a large degree degenerate when galaxies host both power sources. This has been noticed in earlier comparative studies of XDRs and regions with higher U_{CR} values (though only up to $100 \times U_{CR,Gal}$) where only carefully chosen line ratios can distinguish between them (Meijerink et al. 2006). The still larger CR energy densities expected in CRDRs of ULIRGs will further compound these difficulties.

Provided that a powerful X-ray luminous AGN heating up the bulk of the molecular gas in its host galaxy can be somehow excluded (e.g., via hard X-ray observations), any set of molecular lines and ratios that can strongly constrain the temperature of the dense gas UV-shielded phase ($n(H_2) > 10^4$ cm^{-3}) in ULIRGs will be valuable. Indeed, given that in the hierarchical structures of typical molecular clouds, the dense gas regions, (1) lie well inside much larger ones that strongly attenuate far-UV light and (2) cool strongly via molecular line emission because of their high densities, any evidence for high temperatures for the dense gas phase would be an indicator of strong CR heating. In that regard, observations of high-J CO lines such as $J = 6$–5 *and* its ^{13}CO isotopolog have already been proven excellent in revealing CR heated rather than UV/photoelectrically heated molecular gas in galactic nuclei (Hailey-Dunsheath et al. 2008). Irrespective of the particular set of rotational lines used as a "thermometer" of the dense gas, three general requirements must be met: (1) all lines must have high critical densities ($n_{\rm crit} > 10^4$ cm^{-3}), (2) have widely separated $E_{J+1,J}/k_B$ factors, and (3) the J-corresponding lines of at least one rare isotopolog must also be observed (e.g., ^{12}CO and ^{13}CO or C^{32}S and C^{34}S, etc.). The first two requirements ensure probing of the dense gas phase while maintaining good $T_{\rm k}$ sensitivity, and the last one is necessary for reducing well-known degeneracies when modeling only transitions of the most abundant isotopolog which often have significant optical depths. Molecular lines with $n_{\rm crit} \gtrsim 10^5$ cm^{-3} (e.g., HCN, CS rotational transitions) are particularly valuable since, aside from emanating from gas well within typical pre-stellar cores, they trace a phase whose kinematic state is either dictated by self-gravity (e.g., Goldsmith 2001) or has fully dissipated to thermal motions. This constrains the line formation mechanism (and can be used to remove degeneracies of radiative transfer models, e.g., see Greve et al. 2009), but most importantly it reduces the possibility of residual mechanical heating of the dense gas (Loenen et al. 2008) that could mask as CR heating (as both can heat gas volumetrically).

A brief example of such diagnostics can be provided using a large velocity gradient (LVG) code (e.g., Richardson 1985) to compute relative line intensities for dense gas with $T_{\rm k} = (10$–$15)$ K, and $n(H_2) = 10^5$ cm^{-3}, and $T_{\rm k} = (100$–$150)$ K at the same density. In both cases, a gas velocity gradient due to self-gravity is assumed. For the cold gas, the CO and ^{13}CO $(J+1-J)/(3-2)$ brightness temperature ratios are: $R_{(J+1,J)/32} \lesssim 0.7$ for $J+1 \geqslant 4$ ($J = 1$–0, and 2–1 are not considered because they can have substantial contributions from a diffuse non-self-gravitating phase). For the warm gas $R_{(J+1,J)/32} \sim 0.9$–0.95 for $J+1 = 4$–6, while the corresponding ratios for ^{13}CO are $\sim$1–1.3. Similar diagnostics but using multi-J line emission from rarer molecules (and their isotopologs) with much larger dipole moments ($n_{\rm crit} \gtrsim 10^5$ cm^{-3}) such as HCN and H^{13}CN can even better constrain the temperature of dense gas in galaxies. However, their much fainter emission (e.g., HCN lines are $\sim$5–30 times fainter than those of CO) allows their use only for the brightest nearby starburst nuclei (e.g., see Jackson et al. 1995 for an early pioneering effort), and only ALMA will enable such diagnostics for a large number of galaxies in the local and distant universe.

Strong thermo-chemical effects induced by large $U_{\rm CR}$ values and their ability to volumetrically warm large amounts of dense molecular gas can also provide a valuable diagnostic of the temperatures deep inside dense gas cores. For example, global HNC/HCN $J = 1$–0 brightness temperature ratios of $R^{(1-0)}_{\rm HNC/HCN} = 0.5$–1.0 in galaxies can be attributed to an ensemble of PDRs but ratios $R^{(1-0)}_{\rm HNC/HCN} < 0.5$ cannot and imply $T_{\rm k} \geqslant 100$ K (Loenen et al. 2008). Such low ratios are indeed found in ULIRGs but are attributed to turbulent gas heating by SNRs in dense molecular environments (Loenen 2009) which substantially warms the gas in the absence of photons to $T_{\rm k} \geqslant 100$ K which is necessary for the HNC+H$\rightarrow$HCN+H reaction to proceed efficiently and convert HNC to HCN (e.g., Schilke et al. 1992). Unlike the Galaxy where turbulent gas heating has subsided in the dense subsonic gas cores that would emit in these transitions this may not be so in the ISM of ULIRGs, making CR and mechanical heating difficult to distinguish. As mentioned earlier, moving the CRDR molecular line diagnostic to tracers with ever increasing critical densities (and definitely with $n_{\rm crit} \gtrsim 10^5$ cm^{-3}) may be the only way of "breaking" this degeneracy as turbulent heating is expected to become progressively weaker in higher density cores (after all star formation is expected to proceed in dense gas cores whose turbulence has fully dissipated; Larson 2005). Finally, chemical signatures that can uniquely trace the high $U_{\rm CR}$ values in CRDRs using the high ionization fractions expected for their dense gas cores are particularly valuable. Such a very sensitive probe of $\zeta_{\rm CR}$ and $x(e)$ in dense UV-shielded gas is provided by $R_{\rm D} = [{\rm DCO^+}]/[{\rm HCO^+}]$ versus $R_{\rm H} = [{\rm HCO^+}]/[{\rm CO}]$ abundance ratio diagrams where the high CR energy densities and resulting ionization fractions in CRDRs would correspond to very low $R_{\rm D}$ and very high $R_{\rm H}$ values (Caselli et al. 1998). A dedicated study of these issues that explores the unique diagnostic of CRDRs is provided by Meijerink et al. (2010).

Most of the aforementioned tests will acquire additional diagnostic power once ALMA is able to conduct them at high, sub-arcsecond resolution in nearby ULIRGs. It will then be possible to discern whether very warm dense gas with high ionization fractions is localized around a point-like source, the AGN (and is thus due to XDRs), or is well distributed over the SF area of compact systems and is thus starburst-related (see Schleicher et al. 2010 for a recent such study). High-resolution imaging can also directly measure the high brightness temperatures expected for all optically thick and thermalized molecular lines (where $T^{\rm (line)}_{\rm ex} \sim T_{\rm k}$) in CRDRs. Radiative transfer models of emergent CO line emission from a self-gravitating gas phase with $n(H_2) = 10^5$ cm^{-3} and $T_{\rm k} = (100$–$150)$ K typically yield $T_{\rm b}({\rm CO}) \sim (80$–$140)$ K for $J = 1$–0 up to $J = 7$–6, and imaging at a linear resolution of $\Delta L \lesssim 100$ pc (the diameter of gaseous disks in ULIRGs) would be adequate to directly measure them (see Sakamoto et al. 2008 and Matsushita et al. 2009 for early examples). For $z \lesssim 0.05$ (which would include a large number of ULIRGs), such linear resolutions correspond to angular resolutions of $\theta_{\rm b} \sim 0\farcs1$ (for a flat Λ-dominated cosmology with $H_0 = 71$ km s^{-1} Mpc^{-1} and $\Omega_{\rm m} = 0.27$) which would certainly be possible with ALMA.

4. CONCLUSIONS

The main conclusions of this work are as follows.

1. In the high star formation density environments of ULIRGs, CR energy densities $U_{\rm CR}$ will be enhanced by a tremendous factor of $\sim$few $\times(10^3$–$10^4)U_{\rm CR,Gal}$. These will permeate the large molecular gas reservoirs of such systems, likely turning them into CRDRs where CRs, not far-UV photons, regulate the thermal and ionization state of the bulk of their typically very dense molecular gas.

2. Irrespective of whether the very large CR energy densities in the CSB regions of ULIRGs provide the dominant heating for most of their molecular gas or not, they will dramatically raise the gas temperature and ionization fraction minimum values possible in their ISMs, which are typically attained in UV-shielded dense gas cores where the star formation initial conditions are set.
3. The new and very different initial conditions for star formation in CRDRs are an imperative for all high-density star formation events and will almost certainly raise the characteristic mass of young stars (and thus the stellar IMF mass scale) during such events throughout the universe.

Sensitive observations of key molecular lines with high critical densities ($n_{\rm crit} \gtrsim 10^5$ cm^{-3}) as well as high-resolution millimeter/submillimeter interferometric imaging will be key tools in uncovering the high temperatures of the dense UV-shielded gas in CRDRs expected in compact extreme starbursts. Tracers of the very high ionization fractions expected for their dense gas can provide an independent assessment of their presence. All these tests will become possible with ALMA for large numbers of ULIRGs in the local universe.

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