ASSESSING RADIATION PRESSURE AS A FEEDBACK MECHANISM IN STAR-FORMING GALAXIES

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ABSTRACT

Radiation pressure from the absorption and scattering of starlight by dust grains may be an important feedback mechanism in regulating star-forming galaxies. We compile data from the literature on star clusters, star-forming subregions, normal star-forming galaxies, and starbursts to assess the importance of radiation pressure on dust as a feedback mechanism, by comparing the luminosity and flux of these systems to their dust Eddington limit. This exercise motivates a novel interpretation of the Schmidt law, the $L_{IR}-L'_{CO}$ correlation, and the $L_{IR}-L'_{HCN}$ correlation. In particular, the linear $L_{IR}-L'_{HCN}$ correlation is a natural prediction of radiation pressure regulated star formation. Overall, we find that the Eddington limit sets a hard upper bound to the luminosity of any star-forming region. Importantly, however, many normal star-forming galaxies have luminosities significantly below the Eddington limit.

We explore several explanations for this discrepancy, especially the role of “intermittency” in normal spirals—the tendency for only a small number of subregions within a galaxy to be actively forming stars at any moment because of the time dependence of the feedback process and the luminosity evolution of the stellar population. If radiation pressure regulates star formation in dense gas, then the gas depletion timescale is 6 Myr, in good agreement with observations of the densest starbursts. Finally, we highlight the importance of observational uncertainties, namely, the dust-to-gas ratio and the CO-to-H$_2$ and HCN-to-H$_2$ conversion factors, that must be understood before a definitive assessment of radiation pressure as a feedback mechanism in star-forming galaxies.

Key words: galaxies: evolution – galaxies: general – galaxies: ISM – galaxies: starburst – galaxies: stellar content – stars: formation

1. INTRODUCTION

Understanding global star formation is crucial in understanding galaxy evolution and the assembly of the $z = 0$ stellar population over cosmic time. Observations indicate that only a few percent of the available gas reservoir in galaxies is converted into stars per local free-fall time (Kennicutt 1998; Krumholz & Tan 2007). In addition, models of the interstellar medium (ISM) suggest that energy and momentum injected by massive stars could act as a feedback loop by driving supersonic turbulence, which would cause most of the gas to be insufficiently dense to collapse, rendering star formation inefficient (Krumholz & McKee 2005). However, the interaction between star formation and the ISM is not well understood, and a mechanism for the regulation of star formation across the large dynamic range of star-forming environments has not yet been conclusively identified. Proposed mechanisms include supernova explosions, expanding HII regions, stellar winds, cosmic rays, magnetic fields, and radiation pressure on dust (McKee & Ostriker 1977; Matzner 2002; Cunningham 2008; Chevalier & Fransson 1984; Socrates et al. 2008; Kim 2002; Weingartner & Draine 2001; Scoville et al. 2001; Scoville 2003; Thompson et al. 2005, hereafter TQM; Krumholz & Matzner 2009, hereafter KM09; Murray et al. 2010, hereafter MQT; Draine 2010; Hopkins et al. 2010).3

In the case of radiation pressure on dust, UV and optical radiation from OB stars are absorbed and scattered by dust grains and subsequently re-radiated as IR radiation. The dust grains are coupled to the gas of the ISM through collisions and magnetic fields, so radiation pressure on the dust exerts a force on the gas as well (O’dell et al. 1967; Ferrara 1993; Laor & Draine 1993; Murray et al. 2005). On galaxy scales, TQM showed that radiation pressure could constitute the majority of the vertical pressure support in dense starburst galaxies such as ultra-luminous infrared galaxies (ULIRGs). Likewise, models of giant molecular cloud (GMC) disruption predict that radiation pressure is the dominant feedback mechanism regulating star formation in the birth of massive star clusters (MQT; KM09). In this picture, gas in a marginally stable galactic disk collapses to form a GMC and a central compact star cluster. When the stellar mass and luminosity of the cluster exceed the Eddington limit for dust, the overlying gas reservoir is expelled. Thus, the final stellar mass in individual star clusters is regulated by the dust Eddington limit. The centers of ULIRGs and GMC cores are optically thick to both UV and the re-radiated IR photons, which make them ideal candidates for radiation pressure support since essentially all of the momentum from the starlight is efficiently transferred to the gas. Recent observations indicate that the most luminous GMCs in the Milky Way are disrupted by radiation pressure (Murray 2010; Murray & Rahman 2010; Rahman & Murray 2010).

In this paper, we critically assess the theory of radiation pressure regulated star formation by comparing the picture developed by TQM, MQT, and KM09 with the available observations of star-forming galaxies ranging from dense individual star clusters and GMCs, to normal spiral galaxies and starbursts. In Section 2, we describe the current model of radiation pressure feedback. We emphasize the deviations from the simplest version of the dust Eddington limit in assessing radiation pressure regulated feedback that arise from ambiguities in the value of the flux-mean dust opacity, and the tendency for low-density galaxies to have highly intermittent knots or hot spots of star formation across their disks. In Section 3, we compare data from the literature to models of radiative feedback. In Section 4, we discuss our conclusions, the major observational and theoretical uncertainties in our analysis, and the implications of our results.
2. THEORETICAL ELEMENTS

The statement that radiation pressure may be an important feedback mechanism in galaxies is equivalent to the statement that galaxies as a whole or the star-forming subregions within them approach or exceed the Eddington limit for dust,

\[ F_{\text{Edd}} = \frac{4\pi Gc\Sigma}{\kappa_F}, \]  

(1)

where \( F_{\text{Edd}} \) is the Eddington flux, \( \Sigma \) is the surface density of the dominant component of gravitational potential in the star-forming region, and \( \kappa_F \) is the flux-mean opacity. The overall picture is that star-forming regions meet the Eddington limit and self-regulate in analogy with an individual massive star (TQM; see also Scoville et al. 2001; Scoville 2003; MQT; KM09). We would thus naïvely expect to test the theory of radiation pressure regulated star formation by taking the ratio of the observed flux (\( F_{\text{obs}} \)) to \( F_{\text{Edd}} \). However, a direct comparison between the simple theoretical expectation

\[ F_{\text{obs}} / F_{\text{Edd}} \rightarrow 1 \]  

(2)

and the observations is complicated by both theoretical and observational uncertainties. For example, although gas is expected to be the dominant mass component in and around massive star clusters in formation, it is unclear how best to estimate \( \Sigma \) in Equation (1) for unresolved galaxies or unresolved star-forming subregions. Below, we consider both CO and HCN emission (see Section 3; Figures 1 and 2), but the conversion from the luminosity in either of these molecular gas tracers to gas mass where the stars are forming, is highly uncertain. Another uncertainty is the coupling of the radiation field to the gas, which is complicated due to both the non-gray nature of the dust opacity and the clumpiness of the gas on all scales (see Section 2.1 below). Finally, there is an additional complication not readily apparent from the time-independent statement of Equation (2): the star formation rate (SFR) across the face of a large spiral galaxy is highly intermittent so that only a small number of subregions are bright at any time. As discussed by MQT and in detail below (Section 2.2), this intermittency can cause normal star-forming galaxies to appear significantly sub-Eddington (\( F_{\text{obs}} / F_{\text{Edd}} \ll 1 \)) when only their average properties are considered, but much closer to Eddington when a model is used to take this effect into account.

2.1. The Radiation Pressure Force

The coupling between radiation and gas in star-forming environments is complex primarily because the flux-mean opacity \( \kappa_F \) in Equation (1) has a full range of more than 3 dex, depending on whether the spectral energy distribution of the system considered is dominated by UV or FIR light. However, there are two distinct regimes: optically thick to UV but thin to the re-radiated FIR and optically thick to FIR. We call these the “single-scattering” and “optically thick” limits, respectively.

2.1.1. Single-scattering Limit

Regions in the single-scattering limit are optically thick to the UV but optically thin to the FIR (\( \tau_{\text{FIR}} \sim \kappa_{\text{FIR}} \Sigma_g / 2 \)). This limit applies over a wide range in surface density:

\[ \Sigma_g \lesssim 5000 M_\odot \text{ pc}^{-2} \kappa_2^{-1} f_{\text{dg, 150}}^{-1}, \]  

(3)

where \( \kappa_{\text{FIR}} = \kappa_2 f_{\text{dg, 150}} \) is the Rosseland-mean dust opacity with \( \kappa_2 = \kappa / (2 \text{ cm}^2 \text{ g}^{-1}) \) (see Section 2.1.2) and \( f_{\text{dg, 150}} = f_{\text{dg}} \times 150 \) is the dust-to-gas ratio. In the single-scattering limit, UV photons are absorbed once and then re-radiated as FIR photons, which free-stream out of the medium.\(^5\) Since the column-averaged flux-mean optical depth in this limit is always equal to unity, the flux-mean opacity for the single-scattering limit is \( \sim 2 / \Sigma_g \). The Eddington flux is then

\[ F_{\text{Edd}} = 10^8 L_\odot \text{ kpc}^{-2} \left( \frac{\Sigma_g}{10 M_\odot \text{ pc}^{-2}} \right)^2 f_{\text{gas}}^{-1}, \]  

(4)

where \( f_{\text{gas}} = \Sigma_g / \Sigma_{\text{tot}} \) is the gas fraction and \( \Sigma_{\text{tot}} = \Sigma_g + 0.1 \Sigma_\star \) (Wong & Blitz 2002). The wide range of column densities over which this limit is applicable implies that the average medium of most star-forming galaxies, some starbursts, and the GMCs that constitute them is single scattering.

2.1.2. Optically Thick Limit

Dense starbursts and GMCs can reach the high gas surface densities \( \Sigma_g \gtrsim 5000 M_\odot \text{ pc}^{-2} \kappa_2^{-1} f_{\text{dg, 150}}^{-1} \) necessary to become optically thick to FIR photons (\( \tau_{\text{FIR}} \gtrsim 1 \)). In this case, \( P_{\text{rad}} \sim \tau_{\text{FIR}} F_c / \kappa_{\text{FIR}} \) depends on temperature (Bell & Lin 1994; Semenov et al. 2003). The functional form of \( \kappa_{\text{FIR}} \) naturally leads to two regimes: “warm” (\( T < 200 \text{ K} \)) and “hot” (\( 200 \text{ K} < T < T_{\text{sub}} \)) where \( T_{\text{sub}} \sim 1500 \text{ K} \) is the dust sublimation temperature. For typical numbers, the central temperature of a massive, compact star cluster is

\[ T^4 \sim \tau_{\text{eff}}^4 \sim \frac{\kappa_{\text{FIR}} F}{\sigma_{\text{SB}}} \frac{\kappa_{\text{FIR}} M_\star}{8\pi R^2} \frac{M_\star \Psi}{4\pi R^2 \sigma_{\text{SB}}}, \]  

\[ T \sim 290 \text{ K} \frac{1}{10^{1/4}} \frac{\Psi_{10}^{1/4}}{3000} \frac{M_\star^{1/4}}{10^5 M_\odot} \frac{R_{150}^{1/4}}{10^2 \text{ pc}}, \]  

(5)

where \( \tau_{\text{eff}} \) is the effective temperature, \( \kappa_{10} = \kappa / (10^2 \text{ cm}^2 \text{ g}^{-1}) \), \( \Psi_{3000} = 3000 \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \) is the light-to-mass ratio of a zero-age main-sequence (ZAMS) stellar population, \( M_{5,6} = M_\star / (10^6 M_\odot) \), and \( M_{5,150} = M_\star / (10^5 M_\odot) \).

Warm Starbursts. For \( T < 200 \text{ K} \), the Rosseland-mean opacity increases as \( \kappa_{\text{FIR}}(T) \approx \kappa_o T^2 \), where \( \kappa_o \approx 2 \times 10^{-4} \text{ cm}^2 \text{ g}^{-1} \text{ K}^{-2} f_{\text{dg, 150}} \). In this case,

\[ F_{\text{Edd}} \approx \left( \frac{3\pi Gc \sigma_{\text{SB}}}{\kappa_o^2 f_{\text{dg, 150}}^2 f_{\text{gas}}} \right)^{1/2} \sim 10^{13} L_\odot \text{ kpc}^{-2} \left( f_{\text{gas}}^{-1/2} f_{\text{dg, 150}}^{-1} \right) \]  

(6)

Remarkably, the flux necessary to support the medium is independent of \( \Sigma \) (TQM).

Hot starbursts. Intense, compact starbursts may have central temperatures greater than 200 K. The corresponding opacity is roughly constant with temperature: \( \kappa_{\text{FIR}}(T) \approx 5\sim10 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg, 150}} \) for temperatures \( 200 \text{ K} < T < T_{\text{sub}} \). For typical numbers,

\[ F_{\text{Edd}}^{\text{thick}} \sim 10^{15} L_\odot \text{ kpc}^{-2} \left( \frac{\Sigma_g}{10^6 M_\odot \text{ pc}^{-2}} \right)^2 f_{\text{gas}}^{-1/2} f_{\text{dg, 150}}^{-1}. \]  

(7)

\(^5\) Galaxies with surface densities less than \( \sim 5 M_\odot \text{ pc}^{-2} \) will be optically thin with respect to dust. Below this limit, the ionization of neutral hydrogen will become the dominant source of opacity. The large cross-section (\( \sigma_{\text{HI}} \approx 6.3 \times 10^{-18} \text{ cm}^2 \text{ per H atom} \)) implies an incredibly small surface density (\( \Sigma_g \gtrsim 10^{-3} M_\odot \text{ pc}^{-2} \)) is required for the medium to be optically thick to ionizing photons. These ionizing photons transfer momentum directly to the gas on the same order as the momentum transfer due to the single-scattering limit for dust. Thus, we encompass this limit and the single-scattering limit for dust under the same heading.
The high surface densities necessary to enter this regime may only be attained in the parsec-scale star formation thought to attend the fueling of bright active galactic nuclei (AGNs; Sirko 
and Goodman 2003; TQM; Levin 2007).

2.2. GMC Evolution and Intermittency

In order to gauge the importance of GMC evolution and intermittency, we adopt the simple picture presented by MQT that marginally stable ($Q \approx 1$) disks fragment into sub-units on the gas disk scale height ($h$) to form GMCs. An individual star cluster is born, reaches the critical Eddington luminosity threshold, and then expels the overlying gas. Importantly, the timescale for collapse and expansion of the GMC is the disk dynamical timescale, $t_{\text{dyn}}$, which can be much longer than the characteristic timescale for the stellar population to decrease in total luminosity, the main-sequence lifetime of massive stars, $t_{\text{MS}} \sim 4 \times 10^6$ yr. In this picture, a low-density star-forming galaxy with radius $r$ should have $\sim (r/h)^2$ sub-units, but only a small fraction $\xi$ (the “intermittency factor”) should be bright at any one time. If each subregion reaches the Eddington luminosity for a time $t_{\text{MS}}$ and is then dark, and then if a large number of subregions are averaged, one expects

$$\xi \equiv \frac{N_{\text{on}}}{N_{\text{tot}}} \sim \frac{L_{\text{obs}}}{L_{\text{Edd}}} \sim \frac{t_{\text{MS}}}{2t_{\text{dyn}} + t_{\text{MS}}},$$

where

$$t_{\text{dyn}} \sim \left(\frac{3\pi(2h)}{32G\Sigma_{\text{tot}}}\right)^{1/2} \sim 3.5 \times 10^7 \, \text{yr} \, h_{100}^{1/2} f_{\text{gas}}^{1/2} \left(\frac{10 M_\odot \, \text{pc}^{-2}}{\Sigma_g}\right)^{1/2}.$$

$h_{100} = h/(100 \, \text{pc})$, $N_{\text{on}}$ is the number of sub-units that are “on,” and $N_{\text{tot}}$ is the total number of sub-units. For example, the normal star-forming galaxy M51 has an observed bolometric luminosity ($L_{\text{obs}} = 0.2L_{\text{Edd}}$) that is a factor of $\sim 4$ larger than its intermittency-corrected Eddington luminosity ($L_{\text{int}}^{\text{crit}} = 0.05L_{\text{Edd}}$). Although the approximation that the stellar population is bright for a time $t_{\text{MS}}$ and then dark is crude, the parameter $\xi$ gives us a way to judge the importance of intermittency in normal star-forming galaxies.

Note that for higher densities, $t_{\text{dyn}}$ decreases and $\xi \to 1$ at a critical surface density

$$\Sigma_{\text{crit}} \sim \frac{3\pi(2h)}{32G(0.5t_{\text{MS}})h^2} \sim 3 \times 10^3 \frac{M_\odot}{\text{pc}^{-2}} h_{100}^{-1}.$$

which corresponds with a critical midplane pressure $P_{\text{crit}} \sim 5 \times 10^{-8}$ erg cm$^{-3}$ $h_{100}^{-2}$ (see Equation (15)). For $\Sigma_{\text{tot}} > \Sigma_{\text{crit}}$, massive stars live longer than the time required to disrupt the parent sub-unit ($t_{\text{MS}} > t_{\text{dyn}}$). MQT argue that in this regime the massive stars continue to drive turbulence in the gas and maintain hydrostatic equilibrium in a statistical sense until $t_{\text{MS}}$, when the process then repeats until gas exhaustion.

Several additional elements of GMC evolution are important in judging whether or not the star formation of galaxies is regulated by radiation pressure on dust. First, the GMCs collapse from regions of size $h^2$, with total mass $\Sigma_g h^2$, and to a size $R_{\text{GMC}} = h/\phi$. This implies that the surface density of individual GMCs is $\Sigma_{\text{GMC}} \sim \phi^2 \Sigma_g$, where $\phi$ can be $\sim 2$–5 in the Galaxy (MQT). For example, taking $\epsilon_{\text{GMC}} = M_\odot/M_{\text{GMC}}$ ($\propto \Sigma_g$ in the single-scattering limit), $\Psi_{3000}$, and assuming $\kappa_{\text{IR}} \sim \kappa_o T^2$ (appropriate for $T \lesssim 200 \, \text{K}$), one finds that the required gas surface density for a GMC to be optically thin to the FIR is $\Sigma_{\text{GMC}} \sim 7000 \epsilon_{\text{GMC}}^{-1/3} M_\odot \, \text{pc}^{-2}$. This GMC gas surface density would correspond to an average gas surface density for the galaxy that is $\phi^2$ times smaller ($\Sigma_g \sim 350$–1800 $M_\odot \, \text{pc}^{-2}$). Thus, the medium surrounding the central star cluster may be optically thick to the FIR even if the average gas surface density of the galaxy is less than the naive estimate given in Section 2.1.2.

At surface densities in excess of $\tau_{\text{FIR}} = 1$ for the GMCs, the models of MQT rely on the fact that the medium is in fact optically thick to FIR radiation. This is in sharp contrast to the work of KM09, where they argue that the effective optical depth is always $\sim 1$ because instabilities allow the radiation to leak out of otherwise optically thick media. MQT argue that the effective optical depth must be much larger than unity in the GMCs of dense starbursts and ULIRGs for radiation pressure to be effective as a feedback mechanism. In addition, they show that the effective momentum coupling between the radiation and the gas can exceed the naive estimate based on a disk-averaged $\tau_{\text{FIR}}$ by a factor of a few in systems as dense as the putative GMCs in Arp 220 because of the time dependence of the GMC disruption process (see Section 4.3).

3. RESULTS

We compile data of super star clusters, normal star-forming galaxies, local starburst galaxies, ULIRGs, submillimeter galaxies (SMGs), hyper-luminous infrared galaxies, and circumnuclear starbursts to assess feedback from radiation pressure. Below, we test the hypothesis that radiation pressure is dynamically important in galaxies and star-forming subregions by comparing data to the Eddington limit (Section 2) on a variety of physical scales ranging from globally averaged properties of galaxies to individual star-forming subregions within galaxies.

3.1. IR Luminosity versus Molecular Line Luminosity

We show the total IR luminosity $L_{\text{IR}}$ as a function of molecular line luminosity $L_{\text{CO}}$ (Figure 1) and $L_{\text{HCN}}$ (Figure 2) for our sample of star-forming galaxies. $L_{\text{IR}}$ is known to trace the total light from massive stars (e.g., Kennicutt 1998), whereas

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6 We used the $J = 1-0$ line unless only higher order lines were available.
7 Aravena et al. (2008); Becklin et al. (1980); Beelen et al. (2006); Benford et al. (1999); Capak et al. (2008); Carilli et al. (2005); Casoli et al. (1989); Chapman et al. (2005); Chung et al. (2009); Combes et al. (2010); Chapman et al. (2009, 2010); Daddi et al. (2007, 2009, 2010a); Downes & Solomon (1998); Daddi et al. (2007); Gao et al. (2007); Gao & Solomon (1999, 2004a,b); Genzel et al. (2003); Graciá-Carpio et al. (2008); Greve et al. (2005, 2006); Isaak et al. (2004); Kim & Sanders (1998); Knudsen et al. (2007); Mauersberger et al. (1996); Mirabel et al. (1990); Murphy et al. (2001); Neri et al. (2003); Riechers et al. (2006, 2007, 2008, 2009); Sadajena et al. (2008); Sakamoto et al. (2008); Sanders et al. (1991); Schinnerer et al. (2006, 2007, 2008); Smith & Harvey (1996); Solomon et al. (1997); Solomon & Vanden Bout (2005); Walter et al. (2003, 2009); Weil et al. (2001); Yan et al. (2010); Young & Scoville (2002); Yun & Hibbard (2001).
8 In reality, for normal galaxies a fraction of the UV and optical light escapes before being reprocessed by dust, and a fraction of the IR is diffuse and likely not associated with star formation (e.g., Kennicutt et al. 2009; Calzetti et al. 2010). The UV and IR luminosities are roughly equal at a bolometric luminosity of $L_{\text{bol}} = 10^{10} L_\odot$, but the UV luminosity is an order of magnitude larger than the IR luminosity at $L_{\text{IR}} \sim 10^{4.5} L_\odot$ (Martin et al. 2005). Thus, we expect that galaxies with $L_{\text{IR}} \sim 10^{10} L_\odot$ to move closer to the Eddington limit in Figure 1.
Figure 1. IR luminosity as a function of CO line luminosity. The different symbols correspond to different rotational transitions of CO: solid circles ($J = 1–0$), crosses ($J = 2–1$), squares ($J = 3–2$), and triangles ($J = 4–3$). The data are the same in both panels. The lines in the left panel correspond to the single-scattering Eddington limit (solid line; assuming $h = 100$ pc and $r = 10$ kpc; Section 2.1.1) and the single-scattering Eddington limit accounting for intermittency (dot-dashed line; Equation (8)). The lines in the right panel show the optically thick Eddington limit for our preferred value of the Rosseland-mean opacity (shaded region; $\kappa_{\text{FIR}} = 5–10$ cm$^2$ g$^{-1}$ $f_{\text{d,g}}$, 150) and for an enhanced dust-to-gas ratio (dashed line; $\kappa_{\text{FIR}} = 30$ cm$^2$ g$^{-1}$ $f_{\text{d,g}}$, 50). Note that no galaxies are significantly super- or sub-Eddington. We emphasize that it is not possible to determine which limit is applicable without knowing a surface density, so dense star-forming regions can be optically thick at $L'_{\text{CO}} \lesssim 10^9$ K km s$^{-1}$ pc$^2$ and approach the optically thick Eddington limit (see Section 2.1). The single-scattering Eddington limit was calculated by adopting the Galactic CO to H$_2$ conversion factor $X_{\text{MW,CO}} = 4.4 M_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$. The optically thick Eddington limit was calculated by adopting the ULIRG CO to H$_2$ conversion factor $X_{\text{ULIRG,CO}} = 0.8 M_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$.

$L'_{\text{CO}}$ and $L'_{\text{HCN}}$ provide a measure of the total gas mass and dense gas mass, respectively. Under the assumption that the total gravitational potential is dominated by the gas on the physical scales where the stars are forming, the Eddington luminosity is related to $L'_{\text{CO}}$ by

$$L_{\text{Edd}} = \frac{4\pi G c}{\kappa} X_{\text{CO}} L'_{\text{CO}}, \quad (11)$$

where $X_{\text{CO}}$ is the $L'_{\text{CO}}$-to-$M_{\text{H}}$ conversion factor and $\kappa$ is the appropriate flux-mean or Rosseland-mean opacity (either single-scattering or optically thick; see Sections 2.1.1 and 2.1.2). Although counterintuitive, the single-scattering Eddington luminosity lies below the optically thick Eddington limit because the dust opacity is column-averaged and highly non-gray (see Section 2.1). We adopt $X_{\text{MW,CO}} = 4.4 M_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$ for normal galaxies (including a correction factor of 1.36 to account for He; Strong & Mattox 1996; Dame et al. 2001), and $X_{\text{ULIRG,CO}} = 0.8 M_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$ for galaxies with $L_{\text{IR}} \gtrsim 10^{11} L_{\odot}$ (as appropriate for starbursts and ULIRGs; e.g., Downes & Solomon 1998). Similarly, if the majority of the IR luminosity comes from regions where the dense molecular gas dominates the potential, then $L_{\text{Edd}}$ is related to $L'_{\text{HCN}}$ by

$$L_{\text{Edd}} = \frac{4\pi G c}{\kappa_{\text{FIR}}} X_{\text{HCN}} L'_{\text{HCN}}, \quad (12)$$

where we explicitly write $\kappa = \kappa_{\text{FIR}}$ because the critical density for HCN emitting gas is large enough that these regions should
always be optically thick (Section 2.1.2).\textsuperscript{9} In Equation (12), we take an $L'_{\text{HCN}}$ -to-$M'_{\text{H}}$ conversion factor of $X_{\text{HCN}} = 3 M_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$, but we caution that $X_{\text{HCN}}$ is uncertain to a factor of $\sim 3$ (Gao & Solomon 2004a, 2004b; see Section 4.5).

In Figure 1, the lines indicate the Eddington limit for various limiting cases. The lines in the left panel show the single-scattering Eddington limit (solid line) and the single-scattering Eddington limit accounting for intermittency (dot-dashed line) assuming $h = 100$ pc and $r = 10$ kpc (Equation (11)). The shaded region in the right panel is the optically thick Eddington limit (Equation (11) with $\kappa_{\text{IR}} = 5$–10 cm$^2$ g$^{-1}$) and the dashed line shows the optically thick Eddington limit for an enhanced opacity ($\kappa_{\text{IR}} = 30$ cm$^2$ g$^{-1}$ $f_{\text{dg},50}$, where $f_{\text{dg},50} = f_{\text{dg}} \times 50$) due to an assumed higher dust-to-gas ratio in dense star-forming environments. We plot the single-scattering (left panel) and optically thick (right panel) Eddington limits separately for clarity, but the data are the same in both panels. The different symbols indicate various rotational transitions of CO: solid circles ($J = 1$–0), crosses ($J = 2$–1), squares ($J = 3$–2), and triangles ($J = 4$–3).

Note that no galaxies exceed the optically thick Eddington limit and most galaxies are neither significantly super- nor sub-Eddington with respect to the single-scattering Eddington limit. We caution that the applicable Eddington limit for any individual galaxy cannot be determined in this plot due to the lack of surface density measurements, which dictate the optical depth to the FIR and the relevant Eddington limit. For example, high surface density star-forming regions can be optically thick at $L_{\text{CO}} \lesssim 10^9$ K km s$^{-1}$ pc$^2$ and lie to the left of the single-scattering Eddington limit (solid line in left panel) but below the optically thick Eddington limit (shaded region in right panel). For the single-scattering limit, our assumption of $r = 10$ kpc is accurate to a factor of $\sim 5$ for most of the sample, but the single-scattering opacity scales as $r^{-2}$, so it is only accurate to a factor of $\sim 25$. Some compact starbursts have radii much smaller than our assumed radius, so they are optically thick, even at low $L_{\text{CO}}$ and this explains why they exceed the single-scattering limit in the left panel but are below the optically thick limit in the right panel. In addition, note that the optically thick Eddington limit is a hard upper bound to a galaxy’s IR luminosity, which suggests that radiation pressure feedback may set the maximum SFR of a galaxy. In the Eddington-limited model, the scatter in the $L_{\text{IR}}$-$L_{\text{CO}}$ relation may be due to variations in $h$, $X_{\text{CO}}$ (see Section 4.5), the dust-to-gas ratio/metallicity (see Section 4.4.3), the effective radii, and the depth of the stellar opacity.\textsuperscript{10}

The intermittency of star formation will likely affect the Eddington limit for CO-emitting gas (dot-dashed line in left panel). $L_{\text{CO}}$ traces the total molecular gas reservoir including the molecular gas that is not actively participating in star formation, such as GMC envelopes and diffuse intercloud gas. The gas mass relevant for the Eddington limit may be overestimated for galaxies in the single-scattering limit. To account for this, we multiply the Eddington luminosity by the intermittency factor for CO-emitting gas $\xi \sim 0.06$ for the Milky Way value of $X_{\text{CO}}$, $h = 100$ pc, $r = 10$ kpc, and $L'_{\text{CO}} = 10^9$ K km s$^{-1}$ pc$^2$ (see Equation (8) and Section 2.2). The intermittency factor approaches unity when $L_{\text{IR}} \sim 2 \times 10^{11}$ K km s$^{-1}$ pc$^2$ $h_{100} f_{10}^{2} L'_{\text{HCN}}$. Thus, compact star-forming regions, such as the nuclear starbursts of ULIRGs, have $\xi \sim 1$ at low $L_{\text{CO}}$ due to their very small radii (e.g., Downes & Solomon 1998).

Figure 2 shows the $L_{\text{IR}}$-$L'_{\text{HCN}}$ relation for our sample of star-forming galaxies. The shaded region represents the optically thick Eddington limit (Equation (12) with $\kappa_{\text{IR}} = 5$–10 cm$^2$ g$^{-1}$) and the dashed line shows the optically thick Eddington limit for an enhanced opacity ($\kappa_{\text{IR}} = 30$ cm$^2$ g$^{-1}$ $f_{\text{dg},50}$, where $f_{\text{dg},50} = f_{\text{dg}} \times 50$), which may result from a higher dust-to-gas ratio in dense star-forming environments. The circles and crosses correspond to the $J = 1$–0 and the $J = 2$–1 rotational transitions of HCN, respectively.

The $L_{\text{IR}}$-$L'_{\text{HCN}}$ relation (Figure 2) is tight and linear over several orders of magnitude, implying that stars form out of dense gas (Gao & Solomon 2004a, 2004b; Wu et al. 2005). The dense gas fraction ($L'_{\text{HCN}}/L'_{\text{CO}}$) is nearly constant for galaxies with $L_{\text{IR}} \lesssim 10^{11}$ $L_{\odot}$ (Gao & Solomon 2004b), so $L'_{\text{CO}}$ can be used to indirectly trace the dense gas mass $M'_{\text{H}}$. However, the dense gas fraction increases dramatically in luminous infrared galaxies (LIRGs) and ULIRGs ($L_{\text{IR}} \gtrsim 10^{11}$ $L_{\odot}$), so CO does not trace dense gas mass in these galaxies (Gao & Solomon 2004b). HCN, on the other hand, has a critical density for excitation that is $\sim 2$ orders of magnitude larger than that of CO, so it traces dense, optically thick gas in star-forming GMC cores rather than diffuse GMC envelopes. The dynamical time for HCN-emitting gas is much less than the main-sequence lifetime of the most massive stars, so the intermittency factor for HCN-emitting gas will be approximately unity:

$$L'_{\text{HCN}} \approx 2 \times 10^5 \text{yr} \rho_{\text{crit, HCN}} \ll \text{MS} \rightarrow \xi \approx 1,$$

where $\rho_{\text{crit, HCN}} \sim 10^{-19}$ g cm$^{-3}$.

If the picture of radiation pressure feedback is correct, then it should determine the $L_{\text{IR}}$-$L'_{\text{HCN}}$ correlation directly. In fact, both the Eddington limit and the data show a linear relation between $L_{\text{IR}}$ and $L'_{\text{HCN}}$. The galaxies closely follow but do not exceed the Eddington limit for our preferred value of the Rosseland-mean opacity ($\kappa_{\text{IR}} = 5$–10 cm$^2$ g$^{-1}$ $f_{\text{dg},150}$). If the opacity is higher ($\kappa_{\text{IR}} = 30$ cm$^2$ g$^{-1}$ $f_{\text{dg},50}$), then many galaxies are consistent with Eddington and a number are super-Eddington. For any of the values of the opacity that we assume, the general agreement between $L_{\text{IR}}$ and $L'_{\text{HCN}}$ suggests that radiation pressure may play an important role in regulating star formation (Scoville 2003). However, a number of important factors remain uncertain, which we discuss in Section 4.

### 3.2. Molecular Schmidt Law and Radiation Pressure

The Schmidt law is a tight power-law relation between the surface density of SFR $\Sigma_{\text{SFR}}$ and the gas surface density ($\Sigma \propto \Sigma_{\text{H}}^{1.4}$; Kennicutt 1998). Furthermore, Bigiel et al. (2008) found that the Schmidt law for molecular gas is linear within local star-forming galaxies ($\Sigma \propto \Sigma_{\text{H}}^{1}$). In the left panel of Figure 3, we plot $\Sigma_{\text{SFR}}$ versus $\Sigma_{\text{H}}$ for individual apertures of THINGS galaxies (small dots; Bigiel et al. 2008; Helfer et al. 2003; Leroy et al. 2008), THINGS galaxies with H$_2$ detections (open circles), starburst galaxies\textsuperscript{11} (solid circles), M82 super star clusters (stars;

\textsuperscript{9} Using $\rho_{\text{crit, HCN}} \sim 10^{-19}$ g cm$^{-3}$, $\tau_{\text{IR}} \sim \kappa_{\text{IR}} \rho_{\text{crit, HCN}} R$ is larger than unity for scales $R \gtrsim 10^2$ pc and $\kappa_{\text{IR}} \gtrsim 10^2$ cm$^2$ g$^{-1}$.

\textsuperscript{10} Note that previous work by Krumholz & Thompson (2007) and Narayanan et al. (2008) explains the slopes of the $L_{\text{IR}}$-$L_{\text{CO}}$ and $L_{\text{IR}}$-$L'_{\text{HCN}}$ relations by comparing the critical density of the gas tracer to the median density of the ISM.

\textsuperscript{11} Aravena et al. (2008); Becklin et al. (1980); Benford et al. (1999); Capak et al. (2008); Casoli et al. (1989); Chapman et al. (2005); Coppin et al. (2009, 2010); Daddi et al. (2009); Downes & Eckart (2007); Downes & Solomon 2004a, 2004b; Wu et al. 2005).
Figure 3. Star formation rate surface density \( \Sigma_* \) as a function of the molecular gas surface density \( \Sigma_{\text{H}_2} \) (left panel) and radiation pressure as a function of midplane pressure \( P_{\text{mid}} \) (Equation (15)) (right panel). The different symbols represent 750 pc apertures of THINGS galaxies (small dots), THINGS galaxies (open circles), starburst galaxies (solid circles), M82 super star clusters (stars), and the Galactic center star cluster (diamond). The solid line in the \( \Sigma_*-\Sigma_{\text{H}_2} \) plot is the Eddington limit for the single-scattering \( (\kappa = \kappa_0) \) limit. The shaded region corresponds to the optically thick Eddington limit for our preferred value of the Rosseland-mean opacity \( (\kappa_{\text{FIR}} = 5-10 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},150}) \). The dashed line shows the effect of a factor of three increase in the dust-to-gas ratio for the optically thick Eddington limit \( (\kappa_{\text{FIR}} = 30 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},50}) \). In the \( P_{\text{rad}}-P_{\text{mid}} \) plot, the solid line shows the Eddington limit adopting \( \kappa_{\text{FIR}} = 10 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},150} \) for optically thick gas. The dot-dashed lines (both panels) are the intermittent Eddington limit (Equation (8)). The hatched regions (both panels) are the critical surface density or pressure for \( \Sigma_{\text{H}_2} \) and \( P_{\text{mid}} \). The shaded region corresponds to the optically thick Eddington limit for our preferred value of the Rosseland-mean opacity \( (\kappa_{\text{FIR}} = 5-10 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},150}) \). Several more optically thick starbursts will be consistent with or even exceed the Eddington limit for \( \kappa = 30 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},50} \). The rough agreement between starburst galaxies and the intermittent Eddington limit reinforces the likely importance of intermittency. However, the intermittent Eddington limit mildly underpredicts \( \Sigma_* \) and \( P_{\text{rad}} \) at for \( \Sigma_{\text{H}_2} \gtrsim 10 M_\odot \text{ pc}^{-2} \) and \( P_{\text{mid}} \lesssim 10^{-12} \text{ erg cm}^{-2} \), indicating that the effect of intermittency may be overestimated.

McCray et al. 2003; McCray & Graham 2007), and the Galactic center star cluster (diamond; Paumard et al. 2006).

We compare the data with the Eddington limit using \( \Sigma_* \) and \( \Sigma_{\text{H}_2} \) as proxies for the radiation and gravitational pressures,

\[
\frac{4\pi G \Sigma_{\text{H}_2}}{\epsilon \kappa} \times \frac{\Sigma_{\text{H}_2}}{\kappa_{\text{FIR}}} \approx 1.5 \text{ dex of it. The Eddington limit accounting for intermittency (dot-dashed line) appears to agree better with the data than the naive single-scattering Eddington limit, suggesting that intermittency may be an important effect (similarly, Papadopoulos & Pelupessy 2010 showed that time dependence might strongly affect the Schmidt law). As the medium becomes optically thick near the critical surface density for intermittency (hatched region; see Section 2.2), the optically thick Eddington limit \( (\Sigma_{\text{Edd}} \propto \Sigma_{\text{H}_2}/\kappa_{\text{FIR}} \propto \Sigma_{\text{H}_2}) \) provides a firm upper bound to \( \Sigma_* \) for our preferred value of the dust opacity \( (\kappa_{\text{FIR}} = 5-10 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},150}) \). If the dust opacity \( (\kappa_{\text{FIR}} = 30 \text{ cm}^2 \text{ g}^{-1} f_{\text{dg},50}) \) is enhanced due to a higher assumed dust-to-gas ratio, then some galaxies reach the optically thick Eddington limit and a few galaxies exceed it.

In the right panel of Figure 3, we plot the radiation pressure from UV and FIR photons versus the midplane pressure. These pressures will balance each other at Eddington (solid line):

\[
P_{\text{rad}} \approx (1 + \tau_{\text{FIR}}) \frac{F}{c} \sim \rho_{\text{mid}} = \frac{\pi}{2} G \Sigma_{\text{Edd}},
\]

where we take \( \tau_{\text{FIR}} = 0.1 \Sigma_\ast \) (Wong & Blitz 2002). The \( P_{\text{rad}}-P_{\text{mid}} \) plot shows that radiation pressure correlates strongly with midplane pressure over 10 orders of magnitude. The Eddington limit serves as a rough upper limit to \( P_{\text{rad}} \), and most galaxies are within 2 dex of the Eddington limit. We note that some of the THINGS apertures and some dense
starbursts reach or exceed the Eddington limit. For galaxies with $P_{\text{mid}} < P_{\text{crit}}$, the critical midplane pressure (hatched region; see Sections 2.2 and 4.2), we expect that the effects of intermittency are important; however, the intermittency-adjusted Eddington limit (dot-dashed line) underpredicts $P_{\text{mid}}$ for star-forming regions with $P_{\text{mid}} \lesssim 10^{−11.5}$ erg cm$^{−3}$. The intermittency factor may overestimate the importance of intermittency because of the simplifying assumption that subregions are “on” or “off” (see Section 2.2). We also see that galaxies and star-forming regions with $10^{−11}$ erg cm$^{−3} \lesssim P_{\text{mid}} \lesssim P_{\text{crit}}$ tend to fall significantly below the Eddington limit, possibly because our simple parameterization of $\chi_{\text{CO}}$ (see Section 4.5) is overestimating $M_{\text{H}_2}$ (and $P_{\text{mid}}$) for these systems. Radiation pressure becomes increasingly more important in the optically thick limit ($P_{\text{rad}} \gtrsim P_{\text{crit}}$) as some galaxies and star-forming regions meet and exceed Eddington. As expected from Figures 1 and 2, if we assume a larger dust-to-gas ratio and opacity ($\kappa = 30$ cm$^{2}$ g$^{−1}$) potentially appropriate for dusty galaxies, then more of the optically thick starbursts would be super-Eddington.

3.3. Radiation Pressure on Sub-galactic Scales

So far we have evaluated radiation pressure on a galaxy-wide scale; however, the distribution of gas and star formation in galaxies is inhomogeneous. Consequently, the Eddington ratio ($\Gamma = P_{\text{rad}}/P_{\text{mid}}$) will likely vary on sub-galactic scales. We use observations from the THINGS survey (Walter et al. 2008; Leroy et al. 2008; Bigiel et al. 2008) to calculate the Eddington ratio as a function of radius in azimuthally averaged radial bins and for semi-resolved (750 pc) apertures. Since the THINGS galaxies are generally in the single-scattering limit (see Equation (3)), we conservatively adopt the radiation pressure to be $P_{\text{rad}} = P_{\text{IR}}/c$ (see Equation (15)). For the midplane pressure given in Equation (15), the corresponding Eddington ratio is $\Gamma_{\text{tot}} = P_{\text{rad}}/(0.5\pi G \Sigma_{\text{tot}})$. Stars and atomic gas may not contribute significantly to the surface density in regions of active star formation, so we also calculate the Eddington ratio assuming that the midplane pressure depends only on the total gas surface density $\Gamma_{\text{g}} = p_{\text{IR}}/(\pi G \Sigma_{\text{H}_2})$ or the molecular gas surface density $\Gamma_{\text{H}_2} = p_{\text{IR}}/(\pi G \Sigma_{\text{H}_2})$. Intermittency may be important because the THINGS observations cannot resolve individual star-forming regions. We calculate the Eddington ratio corrected for intermittency ($\Gamma_{\text{tot}} = \Gamma_{\text{tot}}/\xi$, see Equation (8)). In Figure 4, we plot $\Gamma_{\text{tot}}$ (open circles), $\Gamma_{\text{H}_2}$ (solid triangles), and $\Gamma_{\text{tot}}$ (open squares) as a function of radius for azimuthally averaged rings. We find that $\Gamma_{g}$ is similar to $\Gamma_{\text{tot}}$, so we omit $\Gamma_{g}$ for clarity.

At intermediate radii ($r \sim 1 \rightarrow 10$ kpc), $\Gamma_{\text{tot}}$ and $\Gamma_{\text{H}_2}$ generally increase from sub-Eddington (around 0.1) to approaching or exceeding the Eddington limit ($\Gamma \sim 1$). $\Gamma_{\text{tot}}$ reaches a maximum Eddington ratio at $r \sim 5–10$ kpc, where

---

**Figure 4.** Eddington ratio ($\Gamma = P_{\text{rad}}/P_{\text{mid}}$) as a function of radius for THINGS galaxies with $\text{H}_2$ detections. $\Gamma_{\text{H}_2} = P_{\text{rad}}/(\pi G \Sigma_{\text{H}_2})$ (solid triangles) and $\Gamma_{\text{tot}} = P_{\text{rad}}/(0.5\pi G \Sigma_{\text{tot}})$ (open circles) represent two ways to calculate the midplane pressure. The open squares ($\Gamma_{\text{tot}}^{\text{int}}$) show the effect of adjusting $\Gamma_{\text{tot}}$ for intermittency (see Equation (8)). $\Gamma_{\text{tot}}$ tends to be sub-Eddington, rising to a peak at $r \sim 5–10$ kpc, and then rapidly falling off. However, $\Gamma_{\text{tot}}^{\text{int}}$ is super-Eddington for $r \gtrsim 1$ kpc in most of the galaxies, suggesting that $\xi$ likely overestimates the importance of intermittency. $\Gamma_{\text{H}_2}$ generally follows the trend of $\Gamma_{\text{tot}}$ in the inner regions of galaxies but increases to super-Eddington values as $\Sigma_{\text{H}_2}$ nears the detection threshold.
it falls off steeply. As the observations near the H$_2$ detection threshold, $\Gamma_{H_2}$ increases rapidly due to a small $\Sigma_{H_2}$ with large error bars (see, e.g., Figure 40 of Leroy et al. 2008), and thus the large value of $\Gamma_{H_2}$ at large $r$ is consistent with Eddington to within the errors on $\Sigma_{H_2}$. For $r > 1$ kpc where $\Gamma_{tot} < 1$, the intermittency factor can boost $\Gamma_{tot}$ up to the Eddington limit, suggesting that intermittency is important.

The $\Gamma < 1$ regions in the inner parts of star-forming galaxies present a challenge for radiation pressure regulated star formation. Intermittency cannot account for the low Eddington ratios of these regions. However, a metallicity gradient, as seen in observations of star-forming galaxies (Muñoz-Mateos et al. 2009), increases the Eddington ratio at small radii (see Section 4.4). A metallicity gradient that rises at smaller radii correlates with a decreasing gradient in $X_{CO}$ (Sodroski et al. 1995; Arimoto et al. 1996) and an increasing gradient in the dust-to-gas ratio (Muñoz-Mateos et al. 2009). We adopt the $X_{CO}$ gradient given by Equation (10) of Arimoto et al. (1996) for data from the Milky Way, M31, and M51 ($\log X/X_e = 0.41[1/r_e - 1]$, where $r_e$ is the effective radius, which we assume to be 7 kpc and $X_e$ is the value of $X_{CO}$ at the effective radius). To account for the dust-to-gas ratio gradient, we use a power-law interpolation between $f_{d,g} = 1/30$ at 0.1 kpc and $f_{d,g} = 1/150$ at 10 kpc, motivated by Figure 15 of Muñoz-Mateos et al. (2009).

In addition, collapsing GMCs enhance the surface density by a factor of $\phi^2$ ($\phi = h/R_{GMC}$; see Section 2.2), making some regions optically thick to FIR radiation. In Figure 5, we show the molecular Eddington ratio as a function of radius for NGC 6946 since this galaxy is well below (≈2 dex) the Eddington limit at small radii (see Figure 4). After accounting for intermittency, an $X_{CO}$ gradient, a dust-to-gas ratio gradient, and a surface density enhancement in the GMCs, we find that $\Gamma_{H_2} \sim 1$ for almost all radii in NGC 6946. We find qualitatively similar results for all of the THINGS galaxies shown in Figure 4 assuming that the metallicity, $X_{CO}$, and dust-to-gas ratio gradients are similar to those adopted for NGC 6946. Thus, it is at least in principle possible to explain the nominally sub-Eddington inner regions of local star-forming galaxies using a combination of these effects.

In Figure 6, we plot the distributions of the individual Eddington ratios for the THINGS apertures (750 pc resolution): $\Gamma_{tot}$ (dotted line), $\Gamma_{H_2}$ (dashed line), and $\Gamma_{tot}^{int}$ (solid line). The distribution of $\Gamma_{tot}$ is peaked around $\Gamma_{tot} \sim 0.1$, and the majority of apertures are sub-Eddington for $\Gamma_{tot}$. The high $\Gamma_{tot}$ tail of the distribution extends above the Eddington limit, with super-Eddington apertures comprising 5% of the total apertures and containing 5% of the total flux. Star-forming regions are unresolved on 750 pc scales, so $\Gamma_{tot}$ should be adjusted to account for intermittency ($\Gamma_{tot}^{int}$). However, most apertures lie above the intermittency-adjusted Eddington limit. As in Figures 1–5, this shift suggests that intermittency is important for radiation pressure supported star formation in normal spirals; however, $\xi$ appears to overestimate the importance of intermittency, possibly due to the simplifying assumption that subregions are either “on” or “off” (see Sections 2.2 and 4.2). The distributions of $\Gamma_{tot}$ and $\Gamma_{H_2}$ are similar, so we do not plot $\Gamma_{H_2}$ for clarity.

The distribution of $\Gamma_{H_2}$ is less peaked and shifted to systematically higher values than the distribution of $\Gamma_{tot}$ with 10% of these apertures radiating at or above the Eddington limit. This is not surprising (given Figure 4) because radiation pressure will likely be more important in $H_2$-dominated star-forming regions. The detection limit for $H_2$ is higher than that for $H_1$, so the distribution of $\Gamma_{H_2}$ contains fewer apertures than $\Gamma_{tot}$. In addition, the apertures with $H_2$ detections tend to be within 0.4R$_{25}$ (Bigiel et al. 2008), so they might have increased metallicities and dust-to-gas ratios with depressed $X_{CO}$ values, which would increase the Eddington ratio (see Figure 5, Sections 4.4 and 4.5). Super-Eddington apertures contain 6% of the total flux in H$_2$-detected apertures across the whole sample; in NGC 6946, for example, super-Eddington apertures contain 10% of the total flux. The super-Eddington apertures indicate that radiation pressure can be dynamically dominant even when individual star-forming regions remain unresolved, suggesting that radiation pressure may be more important on the scale of GMCs and massive star clusters. Finally, we calculated $\Gamma_{H_2}$ assuming that UV photons contribute to the radiation pressure $P_{tot} = (F_{UV} + F_{IR})/c$. The distribution of $\Gamma_{H_2}$ remains nearly the same because star-forming regions have $F_{IR}/F_{UV} \gg 1$, so we refrain from plotting it in Figure 6.

4. DISCUSSION

We have compared globally averaged and resolved observations of star-forming galaxies with theoretical expectations based on the theory of radiation pressure supported star formation (see Section 2). Although the uncertainties are large (see below), our primary findings are as follows.

1. Figures 1–3 show that star-forming galaxies meet, but do not dramatically exceed, nominal expectations for the dust Eddington limit. When some subregions do seem to exceed the Eddington limit (as in the outer regions of galaxies in Figures 4 and 5), we consider this to be consistent with Eddington since trends in the dust-to-gas ratio and CO-to-$H_2$ conversion factor, as well as the large-scale stellar potential and intermittency of the star formation process ($\xi$; Equation (8)) affect the Eddington ratio at order unity.
2. The $L_{IR}$-$L_{HCN}$ plot (Figure 2) provides the strongest evidence for the importance of radiation pressure feedback since $L_{HCN}$ is expected to directly trace the dense actively star-forming gas and $L_{IR}$ traces the total SFR. If radiation pressure in fact dominates feedback, we would expect a one-to-one correspondence between these two quantities, and such a relation is observed (see also Scoville et al. 2001; Scoville 2003). Nevertheless, for typical values of both $\kappa$ in the optically thick limit and the HCN-to-H$_2$ conversion factor, the Eddington limit overpredicts $L_{IR}$ by a factor of $\sim$3–6. This discrepancy may indicate that the dust-to-gas ratio is larger in the dense HCN-emitting regions, or that the HCN-to-$H_2$ conversion factor is smaller (see Section 4.5 below). If radiation pressure feedback regulates star formation, then this relation is in a sense more fundamental than the Schmidt law because HCN-emitting gas is more closely connected with star formation than CO-emitting gas, in contrast to the observations of Leroy et al. (2008) (see their Figure 15). For completeness, we note that variations in the dust-to-gas ratio will not affect the dependence of $t_{gas}$ on $\Sigma_\ast$ in the single-scattering limit, but uncertainties in $\chi_{CO}$, $\xi$, and $\phi$ (see Sections 4.4 and 4.5) might impact the gas depletion timescale.

3. The central regions of all galaxies in Figure 4 are primarily substantially sub-Eddington when a constant dust-to-gas ratio and lower CO-to-$H_2$ conversion factor are applied to all sub-regions without regard to their radial location. If radiation pressure is in fact the dominant feedback mechanism in these regions, a much higher central dust-to-gas ratio and lower CO-to-$H_2$ conversion factor are required (see Figures 4 and 5). It would be particularly useful for testing radiation pressure feedback to produce the same profiles in HCN.

4. The “break” in the observed Schmidt law at $\Sigma_\ast \sim 100$–1000 $M_\odot$ pc$^{-2}$ (see Figure 3; Daddi et al. 2010b) may be due to the transition from the single-scattering limit to the optically thick limit in the GMCs that collapse to form stars, as in MQT.

5. If radiation pressure is the primary feedback mechanism for regulating star formation, then we predict that the Schmidt law will follow the form of Equation (14) (for discussion of $\kappa$ and $\xi$ as well as uncertainties see Sections 2 and 4.2–4.5).

6. A testable prediction of radiation pressure feedback is that all else being equal the SFR should depend linearly on the dust-to-gas ratio in the optically thick limit.

In addition to these points, below we note an implication of radiation pressure feedback that has so far not been stated in the literature (Section 4.1). Finally, in the remaining subsections we highlight the dominant uncertainties in our work as a guide for future research on the importance of radiation pressure feedback in star-forming galaxies.

4.1. Gas Depletion Timescale

The gas depletion timescale, the time required to consume a galaxy’s gas reservoir at the current SFR, is observed to be $\sim$2 Gyr in normal spirals (Kennicutt 1998; Leroy et al. 2008). Radiation pressure sets the gas depletion timescale to be

$$t_{gas} = \frac{M_\ast}{M_\ast + \epsilon_c \kappa^2}{\xi L_{Edd}} = \frac{\epsilon_c \kappa}{4\pi G \xi}.$$  

Using typical numbers for a spiral galaxy in the single-scattering limit, the gas depletion timescale is

$$t_{gas} \sim 2.1 \text{ Gyr} \Sigma_{30}^{-3/2} h_{100}^{1/2},$$

where $\Sigma_{30} = \Sigma_3 / 10$ cm$^{-2}$ and $h_{100} = h / 100$ pc. This normalization of $t_{gas}$ is in good agreement with the observed gas depletion timescale, but Equation (17) predicts that the gas depletion timescale should have a strong dependence on $\Sigma_3$, in contrast to the observations of Leroy et al. (2008) (see their Figure 15). For completeness, we note that variations in the dust-to-gas ratio will not affect the dependence of $t_{gas}$ on $\Sigma_3$ in the single-scattering limit, but uncertainties in $\chi_{CO}$, $\xi$, and $\phi$ (see Sections 4.4 and 4.5) might impact the gas depletion timescale.

Hot starbursts and optically thick subregions (see Section 2.1.2) have intermittency factors that approach unity and nearly constant opacities, so the gas depletion time is approximately constant:

$$t_{gas} \approx 5.7 \text{ Myr} \kappa_{10},$$

where $\kappa_{10} = \kappa_{\text{FIR}} / 10$ cm$^2$ g$^{-1}$. For comparison, Sakamoto et al. (2008) find that the optically thick western nucleus of Arp 220 has a gas depletion time of $\sim$6 Myr. The fact that the gas depletion timescale set by radiation pressure is consistent with the observed gas depletion timescale in spirals and ULIRGs is equivalent to the statement of Figures 1–5 that starbursts approach the dust Eddington limit. In addition, we point out that radiation pressure feedback predicts that the specific SFR (SSFR) will be SSFR $\sim 4\pi G \xi f_{gas} / (\epsilon_c \kappa)$ for small $f_{gas}$.

4.2. Intermittency

The intermittency factor $\xi$ (see Section 2.2; MQT) relates the properties of radiation pressure dominated star-forming subregions to the global properties of a galaxy. However, $\xi$ may overestimate the effect of intermittency in some galaxies.
4.3. The FIR Optical Depth

A key theoretical uncertainty in calculating the Eddington limit for dense starbursts is the effective optical depth ($\tau_{\text{opt}}$) for surface densities where $T_{\text{eff}} > 1$. In order for radiation pressure to be dynamically important in optically thick GMCs, $T_{\text{eff}}$ must exceed unity. Based on the high Mach number turbulence simulations of Ostriker et al. (2001), MQT conclude that if the ISM is optically thick on average, then the vast majority of sight lines will be optically thick. For comparison, KM09 argue that instabilities, such as Rayleigh–Taylor and photon–bubble instabilities, will reduce the effective optical depth of the dense ISM to $\sim 1$. However, MQT note that both the midplane pressure from gravity $P_{\text{mid}} \sim \pi G\Sigma^2$ and optically thick radiation pressure $P_{\text{rad}} \sim \rho F/\epsilon \propto \Sigma^2$, a feature unique to radiation pressure among stellar feedback processes. Thus, if radiation pressure cannot regulate star formation in dense, optically thick gas, then no known stellar feedback process can.

4.4. Dust-to-Gas Ratio and Metallicity

The coupling between radiation and gas directly depends on the dust-to-gas ratio ($\kappa \propto f_{\text{dust}}$). In this analysis, we assume the Galactic value for the dust-to-gas ratio ($f_{\text{dust}} = 1/150$) and solar metallicity; however, there is strong evidence that $f_{\text{dust}}$ and metallicity change with environment. The dust-to-gas ratio has been shown to correlate with metallicity and radius (Issa et al. 1990; Liskenfeld & Ferrara 1998; Draine et al. 2007; Muñoz-Mateos et al. 2009). Muñoz-Mateos et al. (2009) find that the dust-to-gas ratio can climb to values as high as $f_{\text{dust}} \sim 1/10$ in the centers of spiral galaxies. This increase in metallicity and dust-to-gas ratio is necessary for the centers of star-forming spirals to be at the Eddington limit (see Figures 4 and 5 and Section 3.3). The average dust-to-gas ratio of local spirals also varies by a factor of a few (e.g., M51 has a $f_{\text{dust}} \sim 1/75$; Draine et al. 2007). Furthermore, the dust-to-gas ratio is observed to be higher in some dense starbursts, such as SMGs ($f_{\text{dust}} \sim 1/50$; Kovács et al. 2006; Michałowski et al. 2010) and submillimeter faint LIRGs ($f_{\text{dust}} \sim 1/20$; Casey et al. 2009). Importantly, if we adopt a dust-to-gas ratio potentially appropriate for dusty starbursts (short dashed line in Figures 1, 2, and the left panel of Figure 3), then a substantial fraction of optically thick galaxies would be at or above the Eddington limit (Figure 5 illustrates this for NGC 6946).

4.5. Molecular Gas Tracers

The Eddington limit depends strongly on the CO-to-H$_2$ ($X_{\text{CO}}$) and the HCN-to-H$_2$ ($X_{\text{HCN}}$) conversion factors (see Equations (11) and (12)). These conversion factors are two of the largest sources of observational uncertainty in our calculations because they vary with excitation conditions ($X \propto \sqrt{n_{\text{H}_2}/T_b}$, where $T_b$ is the brightness temperature) and metallicity. Several lines of evidence suggest that $X_{\text{CO}}$ overestimates $M_{\text{H}_2}$ in starburst galaxies. For example, $X_{\text{CO}}$ is a factor of $\sim 3$ lower in M82 (Weiβ et al. 2001) and a factor of $\sim 5$ lower in a sample of local ULIRGs (Downes & Solomon 1998). To account for the different values of $X_{\text{CO}}$ in normal spirals and extreme starbursts, we apply the Milky Way $X_{\text{CO}}$ value to galaxies with $L_{\text{IR}} < 10^{11} L_{\odot}$ and the ULIRG $X_{\text{CO}}$ value to galaxies with $L_{\text{IR}} > 10^{11} L_{\odot}$. Because this prescription is somewhat simplistic, it probably overestimates $M_{\text{H}_2}$ in moderate luminosity starbursts ($L_{\text{IR}} < 10^{11} L_{\odot}$), such as M82, and in the centers of star-forming spirals (see Figures 4 and 5 and Section 3.3). Additionally, it likely underestimates $M_{\text{H}_2}$ in ultra-luminous ($L_{\text{IR}} \sim 10^{12} L_{\odot}$) high-redshift disk (BzK) galaxies, for which Daddi et al. (2010a) find a value of $X_{\text{CO}}$ that is consistent with the Galactic value. As a result, moderate luminosity starbursts and the centers of star-forming spirals may be closer to Eddington and BzK galaxies might be further below the optically thick Eddington limit than Figure 3 would suggest.

Unfortunately, $X_{\text{HCN}}$ is more uncertain than $X_{\text{CO}}$ because there is no direct calibration of $X_{\text{HCN}}$ from Milky Way GMCs. For normal spirals, Gao & Solomon (2004a, 2004b) find $X_{\text{HCN}} \sim 10 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ for virialized cloud cores with $(n) = 3 \times 10^4 \text{cm}^{-3}$ and $T_b = 35 \text{ K}$. They caution that $X_{\text{HCN}}$ could be lower in regions of massive star formation due to significantly higher brightness temperatures $T_b \sim \text{few} \times 10^5 \text{ K}$ (Boonman et al. 2001). In addition, Papadopoulos (2007) finds large variations in excitation conditions in LIRGs, suggesting that using a universal $X_{\text{HCN}}$ conversion factor might be a poor tracer of dense gas mass. Ultra-luminous starbursts exhibit widespread intense massive star formation, so one might expect that $X_{\text{HCN}}$ is lower in more luminous galaxies. For example, Graciá-Carpio et al. (2008) estimate that $X_{\text{HCN}}$ should be $\sim 4.5$ times lower for galaxies at $L_{\text{FIR}} \sim 10^{12} L_{\odot}$ than at $L_{\text{FIR}} \sim 10^{11} L_{\odot}$. We note that if $X_{\text{HCN}}$ is smaller than the assumed value of $3 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$, then more galaxies will approach or exceed the Eddington limit (see Figure 2). For example, decreasing $X_{\text{HCN}}$ by a factor of $\sim 2$ brings essentially all galaxies in line with the Eddington limit for the nominal value of $\kappa_{\text{FIR}} (\sim 5–10)$.

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