THE EDDINGTON LIMIT IN COSMIC RAYS: AN EXPLANATION FOR THE OBSERVED FAINTNESS OF STARBURSTING GALAXIES

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ABSTRACT

We show that the luminosity of a star forming galaxy is capped by the production and subsequent expulsion of cosmic rays from its interstellar medium. By defining an Eddington luminosity in cosmic rays, we show that the star formation rate of a given galaxy is limited by its mass content and the cosmic ray mean free path. When the cosmic ray luminosity and pressure reaches a critical value as a result of vigorous star formation, hydrostatic balance is lost, a cosmic ray-driven wind develops, and star formation is choked off. Cosmic ray pressure-driven winds are likely to produce wind velocities significantly in excess of the galactic escape velocity.

It is possible that cosmic ray feedback results in the Faber-Jackson relation for a plausible set of input parameters that describe cosmic ray production and transport, which are calibrated by observations of the Milky Way’s interstellar cosmic rays.

Subject headings: galaxies: formation – galaxies: fundamental parameters – galaxies: starburst

1. INTRODUCTION

In the context of galaxy formation, “feedback” processes are commonly invoked to limit the formation of stars. Feedback can be “intrinsic” or “extrinsic,” where an intrinsic feedback mechanism regulates star formation directly at the molecular cloud level and an extrinsic mechanism controls the supply of stellar fuel on galactic scales.

There is long-standing observational evidence that extrinsic feedback mechanisms operate. For example, the luminosity of local galaxies correlates with the stellar velocity dispersion, and thus gravitational binding energy, of the entire galaxy itself (Faber & Jackson 1976). Two popular extrinsic feedback mechanism are thermally-driven winds powered by core-collapse SNe (see e.g., Chevalier & Clegg 1985; Leitherer et al. 1999) and momentum-driven winds powered by starburst radiation (Scoville 2003, hereafter SCO; Murray et al. 2005, hereafter MQT). In this work, we consider another possibility: galactic winds driven by cosmic rays.

1.1. Basic Idea: The Eddington Limit in Cosmic Rays

There is a theoretical upper-limit on luminosity of gravitationally bound systems, the Eddington limit $L_{\text{edd}}$, given by

$$L_{\text{edd}} = \frac{4\pi GM_{\text{enc}} m_p c}{\sigma_T}$$

(1)

where $M_{\text{enc}}$ is the enclosed mass and $\sigma_T$ is the Thomson cross section. Quasars, the most luminous objects in the Universe, are thought to be powered by accretion onto a black hole and thus their maximum luminosity is given by

$$L_{\text{edd}}^Q \approx 10^{47} M_8 \text{ erg s}^{-1}$$

(2)

where $M_8$ is the quasar black hole mass in units of $10^8 M_\odot$. In the case of elliptical galaxies, the mass of the black hole’s host galaxy is $\approx 10^2 - 10^3$ times that of the black hole (Magorrian et al. 1998). However, rather than being the brightest persistent sources in the Universe, typical luminosities of bright star forming galaxies range from $10^{45} - 10^{46} \text{ erg s}^{-1}$ at least a factor of ten less powerful than their quasar counterparts.

Photons are not the only type of radiation produced from the act of star formation. For every core-collapse supernova, a fraction $\epsilon \sim 0.1$ of the released energy $\sim 10^{50} \text{ erg}$ is converted into cosmic rays (CRs). Unlike photons, cosmic rays interact many times with the interstellar medium, and exchange momentum with it, through pitch-angle scatterings with Alfvén waves. Though the energy injection rate of CRs is insignificant in comparison to other by-products of star formation such as photons, winds, and supernova shocks, the rate at which they inject momentum is not.

In the case of the Milky Way, the CR diffusion time $t_{\text{diff,CR}} \sim 10^7 \text{ yrs}$ over a characteristic scale of $H \sim 1 \text{kpc}$. Thus the characteristic mean free path for a Galactic CR is given by

$$\lambda_{\text{cr}} \sim \frac{3H^2}{c t_{\text{diff,CR}}} \sim 1 \text{ pc},$$

(3)

for 1-10 GeV CRs. Whereas the Thomson mean free path $\lambda_T \sim 10^{24} \text{ cm}$. Thus, CRs are much more highly coupled to the Galactic matter in comparison to photons.

Due to the higher level coupling, the threshold for the maximum allowable CR flux and luminosity is lower in comparison to the electron scattering case. A rough theoretical upper limit for the CR luminosity $L_{\text{edd,CR}}$ is given by

$$L_{\text{edd,CR}} \approx L_{\text{edd}} \frac{\lambda_{\text{cr}}}{\lambda_T} = 10^{-6} L_{\text{edd}}$$

(4)

Ultimately, the ratio $\lambda_{\text{cr}}/\lambda_T$ may be thought of as the ratio of the effective cross section for a CR to interact with a unit of plasma mass divided by the corresponding value for a photon.
1.2. Plan of this work

In the next section we present the main results of this work. First, a brief overview of the observed properties of bright starbursting galaxies is given [22]. The basics of a momentum-driven CR feedback mechanism is given [22, 23] as well, and to some degree in [24, 25] as well, weigh the advantages and disadvantages of the various galactic feedback mechanisms and then compare them to our CR feedback mechanism. In [26] we discuss some of the relevant microphysical properties of CRs that are relevant for CR feedback and in [27, 28] we speculate as to whether or not CR feedback is responsible for the Faber-Jackson (1976) relation. We conclude in [29].

2. Cosmic Ray Feedback in Starbursting Galaxies

Galactic scale CR-driven winds have been studied from a theoretical point of view for many years (see e.g. Ipavich 1975; Breitschwerdt et al. 1991). However to our knowledge, the connection between star formation and wind power as a function environment was not considered.

Recently, CR feedback in galaxy formation has been considered by Jubelgas et al. (2006). They found that CR feedback can quench star formation for low mass galaxies with velocity dispersions $\sigma \leq 80$ km/s. In what follows, we argue that CR feedback potentially chokes off star formation even for galaxies that are much larger, where the velocity dispersion $\sigma$ can reach values up to $\sim 300$ km/s. We believe that our conclusion differs from theirs due to a difference in the handling of CR transport, a point that is discussed in §3.3.

Before we delve into the physics of CR feedback and transport, some of the observed properties of starbursting galaxies are summarized.

2.1. Observed Properties of Starbursting Galaxies

As previously mentioned, galaxies and even starbursting galaxies are dim in comparison to their quasar counterparts. Bright young and gas rich starbursters possess characteristic bolometric luminosities of $L_{\text{bol}} \sim 10^{45} - 10^{46}$ erg s$^{-1}$ at the massive end. Starbursters are powered by UV photons emanating from the surface of massive stars in which the overwhelming majority ($\sim 90 - 99\%$) of the energy release is reprocessed into the infrared, a result of UV opacity onto dust grains.

Although starbursting galaxies exhibit rather complex structure and characteristic properties may vary greatly with location, some representative values of the densities, outflow velocities, and length scales can be obtained from observations. Typical H$_2$ number densities for extreme starburst regions vary between $10^2 - 10^4$ cm$^{-3}$. These densities are representative averages over regions which extend $\sim 100 - 500$ pc from the nucleus (e.g., Downes & Solomon 1998). High velocity winds are a generic feature of starbursts, both locally and at high redshift (Veilleux et al., 2005). Outflow speeds in excess of the escape velocity are commonly observed irrespective of the mass of the host (see e.g., Fig. 7 of Martin 2005). Mass outflow rates can also be estimated, although less robustly. Outflow rates are typically inferred to be anywhere from a few to $\sim 100\%$ of the star formation rate (Veilleux et al. 2005; Martin 2005). These estimates are sensitive to the length scale used to convert the observed gas column to the mass outflow rate, which is difficult to determine.

There is also copious evidence for high velocity winds in the spectra of several $z > 1$ galaxies. This evidence comes from blue-shifted absorption lines and P Cygni Ly$\alpha$ emission line profiles in the rest frame UV spectra (Veilleux et al. 2005). Among these high redshift galaxies, the lensed source, MS 1512-cB58, has the highest quality spectra. The bulk outflow velocity is $255$ km s$^{-1}$, with absorption extending to $\sim 750$ km s$^{-1}$, well above the escape velocity (Pettini et al. 2002). These outflow velocities are not uncommon, and are, in fact, typical of luminous Lyman break galaxies (Adelberger et al. 2003, Shapley et al. 2003).

2.2. Maximum Luminosity of Starbursting Galaxies

As previously mentioned, CRs are an energetically sub-dominant by-product of star formation. But, due to their small mean free path with the magnetized interstellar medium, the collective momentum response with a given galaxy’s gaseous component might have dramatic consequences. In order to determine under what conditions CR production will heavily influence the dynamics of a galaxy, we consider a galactic hydrostatic balance were the CR force is balanced by gravity alone.

For the sake of simplicity and a lack of theoretical and observational constraints, we take a one-zone approach. That is, we collapse all of the information regarding the structure of a given galaxy into a single characteristic value taken at a characteristic length scale. Later on, in §3.3 we justify this approach. Furthermore, from here on, we assume that the mass distribution of a given galaxy resembles that of a singular isothermal sphere whose relevant properties are briefly listed in Appendix A.

For the sake of clarity, we derive the maximum luminosity in CRs – and indirectly photons as well – of young star forming galaxies by examining hydrostatic balance in three different ways.

2.2.1. Hydrostatic Balance

In order for the CRs to limit the inward flow of gas and thus quench star formation, they must be responsible for the bulk of the galactic pressure. In the diffusion limit, the CR pressure is related to the CR flux by the relation

$$ P_{\text{CR}} \simeq F_{\text{CR}} \tau_{\text{CR}} c. $$

(5)

The CR flux $F_{\text{CR}}$ is related to the star formation rate per unit area $\dot{\mu}_{\text{SF}}$ by the relation

$$ F_{\text{CR}} \simeq \epsilon_{\text{CR}} \dot{\mu}_{\text{SF}} c^2. $$

(6)

If we assume the galaxy in question resembles an isothermal sphere, the flux of CRs can be related to a star formation rate within a given radius

$$ F_{\text{CR}} \simeq 10^{-3} \epsilon_{\text{SF}} \dot{\mu}_{\text{SF}} R_{\text{kpc}}^{-2} \text{ erg cm}^{-2} \text{s}^{-1}. $$

(7)

where $\epsilon_{\text{SF}}$, $\dot{\mu}_{\text{SF}}$, $R_{\text{kpc}}$ is the efficiency of converting rest mass into CR energy in units of $10^{-6}$, star formation rate in units of solar masses per year, and galactic radius in units of kpc, respectively.

Now, we may write the CR pressure as

$$ P_{\text{CR}} \simeq 3 \times 10^{-14} \tau_{\text{CR}} \epsilon_{\text{SF}} \dot{\mu}_{\text{SF}} R_{\text{kpc}}^{-2} \text{ erg cm}^{-3}. $$

(8)
In our feedback picture, the outward diffusion of CRs halts gas accretion and thus star formation once CR pressure is almost entirely supporting the gaseous component of the galaxy against the inward force of gravity. In that case, hydrostatic balance dictates

\[ P_{\text{cr}} \simeq \rho \sigma^2 \simeq 3 \times 10^{-7} f_\gamma R_{\text{kpc}}^2 \sigma_{200}^4 \]

for an isothermal sphere. With this, a criteria relating star formation rate and CR optical depth to the mass of the galaxy, or equivalently, its velocity dispersion is given by

\[ \dot{m}_{\text{sf}} \simeq 10^3 \tau_3^{-1} \sigma_6^{-1} f_{\theta_{\text{v}} \text{, isothermal}} \sigma_{300}^2, \]

which does not explicitly depend upon galactic radius. Note that \( \tau_3 \) and \( f_{\theta_{\text{v}} \text{, isothermal}} \) is the CR optical depth in units of \( 10^3 \) and the gas fraction normalized to 0.1, respectively. The value for \( \dot{m}_{\text{sf}} \) in the above expression seems enormous. Interestingly, this is truly an upper limit.

For every gram of matter that is assembled into stars, CRs are responsible for only \( \sim 10^{-5} \) of the energy release while photons are responsible for the overwhelming majority. Consequently, the CR luminosity is smaller than the starburst photon luminosity by a factor of \( \sim 10^3 \). Motivated by the assumption that every UV photon released from the surface of a massive star is absorbed by dust grains and subsequently downgraded into non-interacting infrared radiation, MQT employ the “single scattering approximation,” which sets the photon optical depth \( \tau_\gamma = 1 \) for all galaxies. If \( \tau_{\text{cr}} \sim 10^3 \) as in the case of the Milky Way, then the maximum star formation rate, CR luminosity, and photon luminosity given by eq. [13] is equal to the upper limit derived by MQT in the case that photons feedback determines the maximum galactic luminosity.

Note, that we have yet to consider the dependencies of bulk galactic properties such as the velocity dispersion \( \sigma \) and gas fraction \( f_\gamma \) upon the optical depth \( \tau_{\text{cr}} \) and efficiency \( \epsilon_{\text{cr}} \).

2.2.2. (Cosmic) Radiation-Pressure-Driven Wind

Instead of balancing CR pressure with gravity, we now phrase hydrostatic balance in terms of the CR luminosity and enclosed mass. Again, by assuming spherical symmetry, hydrostatic balance is given by

\[ \frac{\kappa_{\text{cr}}}{c} F_{\text{cr}} \equiv \frac{\kappa_{\text{cr}} L_{\text{cr}}}{c 4 \pi r^2} \simeq \frac{GM(r)}{r^2}. \]

If we integrate over mass i.e., \( dm = \rho d^3x = 4 \pi \rho r^2 dr \), then opacity may be replaced with optical depth. We have (see e.g., Lamers & Cassinelli 1999)

\[ L_{\text{cr}} \tau_{\text{cr}} \simeq \frac{f_\gamma G M^2(r) \sigma_{200}^2}{R^2} \]

(12)

If the mass distribution of the galaxy in question resembles an isothermal sphere, we have

\[ L_{\text{cr}} \tau_{\text{cr}} \simeq \frac{4 \pi f_\gamma}{G} \sigma_4. \]

In terms of typical scalings for galaxies

\[ L_{\text{cr}} \tau_{\text{cr}} \simeq 3 \times 10^{46} f_{\theta_{\text{v}} \text{, isothermal}} \sigma_{200}^2 \text{erg s}^{-1} \]

(14)

where \( f_{\theta_{\text{v}} \text{, isothermal}} \) and \( \sigma_{200} \) are the gas fraction and velocity dispersion normalized to value of 0.1 and 200 km s\(^{-1}\), respectively. Note that eq. [14] is identical to eq. [10].

For every gram of matter that is assembled into stars, CRs are responsible for only \( \sim 10^{-5} \) of the energy release while photons are responsible for the overwhelming majority. Consequently, the CR luminosity is smaller than the starburst photon luminosity by a factor of \( \sim 10^3 \). Motivated by the assumption that every UV photon released from the surface of a massive star is absorbed by dust grains and subsequently downgraded into non-interacting infrared radiation, MQT employ the “single scattering approximation,” which sets the photon optical depth \( \tau_\gamma = 1 \) for all galaxies. If \( \tau_{\text{cr}} \sim 10^3 \) as in the case of the Milky Way, then the maximum star formation rate, CR luminosity, and photon luminosity given by eq. [13] is equal to the upper limit derived by MQT in the case that photons feedback determines the maximum galactic luminosity.

Note, that we have yet to consider the dependencies of bulk galactic properties such as the velocity dispersion \( \sigma \) and gas fraction \( f_\gamma \) upon the optical depth \( \tau_{\text{cr}} \) and efficiency \( \epsilon_{\text{cr}} \).

2.2.3. The Eddington Limit in Cosmic Rays

Now, we exchange CR optical depth \( \tau_{\text{cr}} \) with CR opacity \( \kappa_{\text{cr}} \) in order to obtain an equivalent expression for the maximum CR luminosity \( L_{\text{cr}} \). In order to do so, we must determine the effective cross section or mean free path that a typical CR has with magnetized interstellar matter.

Let us take the 1-10 GeV CR mean free path to be \( \lambda_{\text{cr}} \sim 1 \text{ pc} \), approximately the Milky Way value, as a benchmark. In order to obtain an Eddington limit, we compare the CR mean free path \( \lambda_{\text{cr}} \) to the Thomson mean free path \( \lambda_T \) i.e.,

\[ L_{\text{edd,cr}} \simeq \frac{\epsilon_{\text{cr}} \lambda_{\text{cr}}}{\lambda_T} = 4 \pi G c M(r) \rho(r) \lambda_{\text{cr}} \]

(15)

or

\[ L_{\text{edd,cr}} \simeq 3 \times 10^{43} \lambda_{\text{cr}} f_{\theta_{\text{v}} \text{, isothermal}} \sigma_{200}^2 R_{\text{kpc}}^{-1} \text{erg s}^{-1} \]

(16)

where \( \lambda_{\text{cr}} \) is the CR mean free path in units of a parsec.

The arguments surrounding eq. [15] are identical to the Eddington argument put forth by Scoville (2003, hereafter SCO) regarding UV photon opacity on dust. His primary motivation was to ascertain the supposed common origin of the light to mass ratio \( L/M \sim 500 L/\odot/M/\odot \) of both self-gravitating giant molecular clouds in M51 and the central region of the dusty luminous starburst galaxy Arp 220.

We define a CR to mass ratio \( R_{\text{cr}} = L_{\text{cr}}/M(r) \), which for an isothermal sphere is given by

\[ R_{\text{cr}} \simeq 2 f_{\theta_{\text{v}} \text{, isothermal}} \sigma_{200}^2 R_{\text{kpc}}^{-1} \lambda_{\text{cr}} R/\odot. \]

(17)

where \( R/\odot = L/\odot/M/\odot \sim 2 \text{ erg s}^{-1} \text{g}^{-1} \) is the light to mass ratio of the Sun. If the efficiency of generating photon power from the act of star formation is \( \epsilon_{\text{sf}}/\epsilon_{\text{cr}} \sim 10^3 \), then the upper limit for the mass to light ratio of starbursting environment, \( R_{\text{sf}} \), is given by

\[ R_{\text{sf}} \simeq \frac{\epsilon_{\text{sf}}}{\epsilon_{\text{cr}}} R_{\text{cr}} \simeq 2 \times 10^3 f_{\theta_{\text{v}} \text{, isothermal}} \sigma_{200}^2 R_{\text{kpc}}^{-1} \lambda_{\text{cr}} R/\odot. \]

(18)

The gas fraction \( f_{\theta_{\text{v}} \text{, isothermal}} \sim 1 \) for both sets of environments considered by SCO. For a CR mean free path \( \lambda_{\text{cr}} \sim 1 \text{ pc} \), the above value for \( R_{\text{sf}} \) is reasonably close to the measured value for Arp 220, given that the velocity dispersion...
of Arp 220 is slightly different than $\sigma_{200}$, the mass distribution is not perfectly described as an isothermal sphere, and the observed $L_{\text{SF}}$ (or the bolometric luminosity) is only accurate to a factor of 2 or so. Giant molecular clouds have typical dimensions of $\sim 10-30$ pc and velocity dispersion $\sigma \lesssim 10$ km s$^{-1}$. Therefore, according to the form of $R_{\text{SF}}$ given by eq. (18), both systems will be limited to a similar light to mass ratio resulting CR feedback. In Appendix D we discuss the viability of intrinsic CR feedback in giant molecular clouds.

2.3. Cosmic Rays vs. Photons and Supernovae

Now, we assess how the three major by-products of star formation i.e., starlight, supernovae, and cosmic rays compare with one another in terms of their ability to inject momentum into the interstellar medium. Special attention is given when comparing CRs and photons. Our arguments are given below.

2.3.1. Global Kinematics of Various Feedback Mechanisms

Energetically, cosmic rays are a highly subdominant by-product of star formation. However, if the injection of momentum determines whether or not the star forming constituents disrupt the galaxy of their birth, then energy deposition is not the determining factor. At the crudest possible level of discourse, the rate at which momentum is deposited in a galaxy $\dot{P}$ is given by

$$\dot{P} \sim \dot{E}/v \sim L/v$$  \hspace{1cm} (19)

where $v$ is the characteristic velocity at which the energy carrying particles are transported.

As previously mentioned, $L_{\text{SF}} > L_{\text{SN}} > L_{\text{CR}}$. However at the same time, $c > v_{\text{SN}} > v_{\text{CR}}$. In the case of core-collapse SNe,

$$\dot{P}_{\text{SN}} \sim L_{\text{SN}}/v_{\text{SN}} \sim 10^{33} m_{\text{SN}} \text{ g cm}^{-2} \text{ s}^{-2}$$  \hspace{1cm} (20)

where $v_{\text{SN}} \sim 3 \times 10^6$ cm s$^{-1}$ is the characteristic velocity of a supernova shock.

For cosmic rays,

$$\dot{P}_{\text{CR}} \sim L_{\text{CR}}/v_{\text{CR}} \sim L_{\text{CR}} \tau_{\text{CR}}/c$$  \hspace{1cm} (21)

$$\sim 3 \times 10^{33} \epsilon_{\text{CR}} m_{\text{SF}} \text{ g cm}^{-2} \text{ s}^{-2},$$

which is slightly larger than the value obtained from supernovae. Here, $v_{\text{CR}} \sim H/t_{\text{diff,Cr}} \sim 10^7$ cm s$^{-1}$ is the characteristic velocity at which cosmic rays diffuse in bulk. Note that $v_{\text{CR}} \sim c/\tau_{\text{CR}}$, where $\tau_{\text{CR}}$ is the optical depth to cosmic rays given by $\tau_{\text{CR}} \sim H/\lambda_{\text{CR}} \sim 3 \times 10^4$ for the Milky Way.

In the case of starlight,

$$\dot{P}_{\text{SF}} \sim L_{\text{SF}}/c \sim 5 \times 10^{32} m_{\text{SF}} \text{ g cm}^{-2} \text{ s}^{-2}.$$  \hspace{1cm} (22)

Therefore all three forms of momentum deposition are comparable. If the photons are optically thick, then $c \rightarrow c/\tau_{\gamma}$ in the above expression where $\tau_{\gamma}$ is the photon optical depth.

2.3.2. Cosmic Rays vs. Photons

Eqs. (10), (14) and (18) all arrive at the same conclusion i.e., for a CR mean path $\lambda_{\text{CR}} \sim 1$ pc and radiative efficiency $\epsilon_{\text{CR}} \sim 10^{-6}$ – values that are reasonably close to the Milky Way value – then, 1-10 GeV CRs will inevitably unbind a given galaxy’s gaseous component. However, eqs. (10), (14) and (18) also inform us that for the same choice of parameters, the basic observational signature of CR feedback – a maximum value for the equivalent physical quantities $\dot{m}_{\text{SF}}, L_{\text{SF}}$ and $R_{\text{SF}}$ – simultaneously indicate that it is photon-feedback, according to the theory of SCO and MQT, that caps the luminosity of a given galaxy.

To our knowledge, there is no simple straightforward observational test that distinguishes between the CR mechanism presented in this work and the photon-driven theory. However, some distinction can be made on theoretical grounds alone.

The advantage of utilizing starburst photons as a feedback mechanism, which limits the star formation, is that the overwhelming majority of the energy and power ($\sim 99\%$) from the action of assembling gas into stars is released in the form of photons. At the same time only $\sim 1/1000$ of the energy release and power from star formation comes out in the form of CRs. Furthermore, the coupling between starburst photons and dusty matter is relatively well understood: UV starlight is absorbed by dust grains and immediately downgraded into non-interacting infrared radiation. The frequency-weighted opacity for this process is roughly a few hundred times the Thomson opacity (SCO; MQT). Finally, measurements of the bolometric photon luminosity of gas-rich starbursting environments directly constrain any photon-feedback theory.

The major uncertainty in a theory of CR feedback is the value of $\tau_{\text{CR}}$ for a given galaxy. In order to unbind interstellar matter in the largest and most massive galaxies, the CR mean free path $\lambda_{\text{CR}} \sim 1$ pc or smaller, which implies that the CR optical depth $\tau_{\text{CR}}$ must be large such that $\tau_{\text{CR}} \sim 10^3$, or even higher. Therefore, any theory of galaxy feedback regulated by CRs requires, as in the case of the Milky Way, a large CR optical depth.

This allows us to raise a crucial point: Due to their large optical depth, each individual CR injects momentum into the interstellar medium in the direction opposite a given galaxy’s gravitational center. Thus, the CR flux and pressure gradient do not strongly depend on the spatial distribution of injection sites. Furthermore, the fact that $\tau_{\text{CR}}$ must be large implies that the one-zone model formulation invoked in §2.2.1–2.2.3 is well justified at the order unity level.

The momentum recoil of the interstellar medium resulting from the absorption of UV starlight onto dust grains strongly depends on the spatial distribution of the photon injection sites. To demonstrate this, we relax an important simplifying assumption employed by SCO and MQT i.e., approximating that the entirety of a given galaxy’s UV radiative flux emanates from a single centrally located point.

In the Milky Way, for example, there are $\sim 10^4$ O stars (Wood & Churchwell 1989) and for young stellar populations with a Salpeter IMF, O stars dominate the radiative power. For the sake of our argument, we assume that each individual O star is embedded in a molecular cloud-like environment for the overwhelming majority of its life. Note that this is not the case in the Milky Way, but is likely to be a good approximation in a gas-rich starbursting galaxy. As previously mentioned, UV starlight from
embedded massive stars is reprocessed and downgraded into the infrared by absorption onto dust grains (Churchwell 2002). It is this source of opacity upon which SCO and MQT build their theory. By doing so, they conclude that starburst photons enjoy a relatively large momentum coupling with the gaseous component of their parent galaxy.

In Appendix B, we briefly outline why the one-zone approximation – meaning that the UV photons originate from a single point – of SCO and MQT qualitatively and quantitatively breaks down on galactic scales. The observational consequence is that starlight can only “stir up” the gas to characteristic velocities of order \( v \sim 1/10 \) of the velocity dispersion \( \sigma \) on length scales of order \( \Delta x \sim 10 \) pc, respectively. It follows, that the starburst luminosity would have to be \( \sim 100 \) times larger than the maximum starburst luminosity \( L_M \) given by MQT if the onset of a photon-driven wind is to limit the luminosity of a galaxy. If this were the case, the bolometric luminosities of galaxies would be \( \sim 10 \) – \( 100 \) times larger than their respective quasars, which clearly violates current observations.

2.4. Aspects of Galactic Scale CR-Driven Winds

As stated in §2.4, starbursters display outflows with velocities significantly in excess of the escape speed \( v_{\text{esc}} \) or the velocity dispersion \( \sigma \). Interestingly, line-driven winds of massive stars and dusty radiation-driven winds of asymptotic giant branch stars also display fast winds with velocities in excess of \( v_{\text{esc}} \).

Radiation (or cosmic radiation) pressure driven winds occur when the luminosity of the source approaches and surpasses the frequency-averaged Eddington limit i.e., when the radiation force exceeds gravity. If the radiatively supported source is in hydrostatic balance beneath its photosphere, then a wind can only develop if the opacity increases above the main body’s photosphere. For example, in the winds of AGB stars, the fact that dust sublimates at temperatures below the photospheric temperature leads to an opacity increase with decreasing density (Salpeter 1974; Goldreich & Scoville 1976; Ivezic & Elitzur 1995).

More specifically,

\[
\rho \frac{\kappa F}{c} = \frac{F}{\lambda c} = \rho g + \rho v \frac{dv}{dr} \tag{23}
\]

where \( \kappa, \lambda, F, v, \) and \( g \) is the radiation opacity, mean free path, flux, outflow velocity, and gravitational acceleration, respectively. If \( \kappa \) increases with decreasing density, then the ratio of radiative to gravitational acceleration increases as a parcel of gas moves outwards. Integrating over volume allows us to write

\[
4\pi \int_{R_0}^{\infty} r^2 dr \left( \frac{F}{\lambda c} - \rho g \right) \geq \frac{L}{c} \tau_w = \dot{M} v_\infty \tag{24}
\]

i.e., infinite acceleration may occur in the limit of infinite optical depth. Here, \( \tau_w \) is the optical depth of the wind, \( \dot{M} = 4\pi R^2 \rho v \) is mass loss rate, \( v_\infty \) is the terminal velocity, and \( R_0 \) is the launching radius. In the above expression, the gravitational acceleration is neglected in the second term since it is assumed to be small in comparison to the radiative acceleration. Of course, \( \tau_w \) limited by energy conservation, which we discuss in Appendix C.

The scenario outlined above for radiatively-driven winds of stars may analogously occur for CR-driven galactic winds. Cosmic ray transport in the Milky Way is often modeled with a constant diffusivity over a large rarefied kpc halo; a picture that is consistent with observations of the galactic CR distribution. Since the diffusivity varies little – or not at all – with density, the CR cross section and thus opacity, increases with decreasing density.

In C we discuss how the CR mean free path and cross section directly depend only upon the magnetic field fluctuations at the Larmor scale. That is, the level of coupling between CRs and matter is, in principle, independent of column density – an ideal situation for winds with multiple scatterings. For example, if the streaming instability is the source of resonant magnetic fluctuations (see §2.3.2), then \( \kappa_{\text{CR}} \propto \rho^{-1/2}/B \), where \( \kappa_{\text{CR}} \) is the CR “opacity.”

As stated in §2.3.2, UV photons released from the surface of massive stars are absorbed and then quickly downgraded into effectively non-interacting IR photons. Therefore, \( \tau_{\gamma} \sim 1 \) for photon feedback – if one accepts an idealized one-zone approximation (see §2.4.1). When the momentum of the radiation field is so weakly coupled to the matter, it is difficult to imagine how photon-driven feedback leads to wind velocities in excess of \( v_{\text{esc}} \) by a factor of \( \sim 10 \), unless the light to mass ratio exceeds that of eq. (15) by a factor of \( \sim 10 \) or so, since the maximum luminosity \( L_M \propto \nu^2 \) for a fixed enclosed mass \( M \) according to formalism of MQT (see e.g., their eq. (26)).

Independent of galactic mass, SNe shocks heat interstellar gas to temperatures of about \( \sim 1 \) keV, which corresponds to a sound speed of \( \sim 300 \) km/s (Martin 1999, 2004). If SNe lead to a thermally-driven wind that is responsible for ejecting the interstellar medium, then the outflow velocity cannot surpass the sound speed. It follows that thermally-driven winds from SNe are unlikely candidate for explaining fast \( \gtrsim 300 \) km/s galactic winds.

2.4.1. Upper Limit on \( \tau_{\text{CR}} \) from Momentum and Energy Conservation

Even in our Galaxy, the interpretation of direct and indirect measurements of CR transport may lead to qualitatively different pictures as to how CR diffuse through the Milky Way and its corona-like halo. Nevertheless, we may roughly set some limits on the CR optical depth \( \tau_{\text{CR}} \) without knowing the details of the particular mechanism responsible for the resonant scatterings.

In the Appendix C, we briefly estimate an upper limit on \( \tau_{\text{CR}} \), following a well established result from the stellar winds literature (Lamers & Cassinelli 1999; Ivezic & Elitzur 1995; Salpeter 1974). For optically thick radiation-driven winds, momentum and energy conservation set an upper limit for the wind optical depth roughly as \( \tau_{\text{CR}} \sim c/v_w \), where \( v_w \) is the wind terminal velocity.

The maximum value of \( \tau_{\text{CR}} \) takes on interesting values when \( v_w \) is large enough as to merit escape from a given galaxy’s gravitational potential. As previously mentioned, since CRs inject roughly \( \sim 1 \) keV/baryon into the interstellar medium, the deepest gravitational potential from which they can unbind gas corresponds to a velocity dispersion \( \sigma \sim 300 \) km s\(^{-1}\). If \( v_w \sim \sigma \), then the corresponding optical depth is \( \tau_{\text{CR}} \sim 10^3 \), which – depending on the interpretation of the CR data – is close
to the Milky value.

3. PHYSICAL PROPERTIES OF COSMIC RAYS

For lack of a better choice, we use the Galaxy in order to calibrate the properties of cosmic ray injection, transport, and star formation in general.

Cosmic ray protons within the relatively modest energy scale of $\sim 1 - 10$ GeV are responsible for $\sim 90\%$ of the Galactic CR pressure near the solar neighborhood. Above 10 GeV, the CR energy energy spectrum $n(E)$ is well described by a single power law such that $n(E) \propto E^{-n}$ from $\sim 10 - 10^6$ GeV. As already implied, the CR spectrum is steep such that $n > 2$, with a commonly quoted value of $n \approx 2.7$.

The distribution of Galactic CRs is highly isotropic such that the energy-weighted CR mean free path $\lambda_{\text{CR}} \sim 0.1 - 1$ pc. This remarkably low value for $\lambda_{\text{CR}}$ is most likely the result of CRs scattering off of magnetic irregularities. Then, for typical Galactic scale height $H \sim 1$ kpc, the interstellar matter of the Galaxy may be considered as possessing an optical depth to CRs $\tau_{\text{CR}} \sim 10^3 - 10^4$. Therefore, the CR pressure $P_{\text{CR}}$ is related to the CR flux $F_{\text{CR}}$ by the simple relation

$$P_{\text{CR}} \approx F_{\text{CR}} \frac{\tau_{\text{CR}}}{c} \ (25)$$

over a CR pressure scale height.

In the Galaxy, a core-collapse supernova occurs once every century, leading to a core-collapse supernova luminosity $L_{\text{SN}}$.

$$L_{\text{SN}} \sim 10^{51} \text{erg}/10^2 \text{yrs} \sim 3 \times 10^{41} \dot{n}_{\text{sf}} \text{ erg s}^{-1} \ (26)$$

where $\dot{n}_{\text{sf}}$ is the normalized star formation rate in units of $1M_\odot/\text{yr}$. The injection of CRs results primarily from the interaction of supernova shocks with the interstellar medium (Ginzburg & Syrovatskii 1964). However, CR deposition from other types of starburst outflows, such as stellar winds from massive stars, may also significantly contribute (Schlickeiser 2002). In terms of the star formation rate $\dot{n}_{\text{sf}}$ and an CR efficiency $\epsilon_{\text{CR}}$, we may write the CR luminosity as

$$L_{\text{CR}} = \epsilon_{\text{CR}} \dot{n}_{\text{sf}} c^2 = 6 \times 10^{40} \epsilon_0 \dot{n}_{\text{sf}} \text{ erg s}^{-1}. \ (27)$$

where $\epsilon_0$ is equal to $\epsilon_{\text{CR}}$ in units of $10^{-6}$ or in other words, $L_{\text{CR}}$ is normalized to $\sim 20\%$ of $L_{\text{SN}}$.

3.1. Observational Constraints on $\lambda_{\text{CR}}$ from the Leaky Box and Galactic Halo Models

Upper limits on the anisotropy of the CR distribution function, the relative abundances of primary to secondary CRs, and the abundance ratios between the radioactive isotopes of a given CR species sum up the directly available observations of CR transport (Schlickeiser 2002). Indirect tracers of CR behavior include radio emission, presumably powered by bremsstrahlung and synchrotron losses of CR electrons, as well as gamma-ray emission resulting from the decay of mesons produced in proton-proton collisions. Altogether, these observational constraints indicate that CRs stay in contact with the Milky way for times scales in the neighborhood of $10^7$ yrs.

Though the direct and indirect observations of CR transport dictate that CRs scatter $\tau_{\text{CR}}^2 \sim 10^6 - 10^8$ times before leaving the Milky Way, they do not uniquely determine the volume of the region in which they are confined (see e.g., Ginzburg et al. 1980). In the one-zone model, or “grammage” formulation, two important pieces of information can be extracted; the CR abundance ratio between CR protons $n_p / n_\text{CR}$ and the average hydrogen number density $\langle n_H \rangle$ during its encounters with the interstellar medium. For $\sim 1 - 10$ GeV CR protons $\langle n_H \rangle \sim 0.2 \text{ cm}^{-3}$ - significantly smaller than average value for the $\sim 100$ pc scale height gaseous disk, where is $n_H \sim 1 \text{ cm}^{-3}$. In the grammage formulation, typical residence timescales in the disk are of order $\sim 3 \times 10^6$ yrs. Together, this implies an optical depth in the disk of $\tau_{\text{CR}} \sim 10^4$ and a mean free path of order $\lambda_{\text{CR}} \sim 0.1 \text{pc}$. The average hydrogen number density $n_H \sim 1 \text{ cm}^{-3}$ for the 100 pc disk, which implies CR protons must somehow avoid regions of relatively large density while maintaining a small level of spatial anisotropy, of order one part in $10^3 - 10^4$. The mass distribution of the Milky Way is partitioned into several different phases of various densities and temperatures. Even if CR protons mainly restrict themselves to a phase with characteristic hydrogen number density $n_H \sim 0.2 \text{ cm}^{-3}$, it seems unlikely that such a phase of the interstellar medium is homogeneously distributed in space at the one part in $10^3$ level, in the solar neighborhood.

In light of the difficulties with the one-zone interpretation of grammage measurements, another scenario that is often used to interpret grammage measurements is the disk + halo model (Ginzburg & Syrovatskii 1964; Ginzburg et al. 1980). By modeling the vertical profile of the Galaxy, the quantitative interpretation of a CR proton’s trajectory is much different in comparison to one-zone disk models. Here, 1-10 GeV CR protons are thought to be rather uniformly distributed in a diffuse $\sim 1$ kpc disk with typical hydrogen number densities $n_H \sim 0.1 \text{ cm}^{-3}$, with a characteristic escape time of order $\sim 10^7$ yrs (Strong & Moskalenko 1998; Webber & Soutoul 1998). In this picture the CR mean free path $\lambda_{\text{CR}} \sim 1 \text{pc}$.

3.2. The Source of Small Scale Resonant Magnetic Irregularities or: A Great Uncertainty in Cosmic Ray Physics

3.2.1. Streaming Instability

CRs flow freely along large scale laminar magnetic fields as they tightly gyrate about their guiding centers. In the presence of small scale magnetic fluctuations, the CRs themselves can amplify waves in which they are resonant, a phenomena known as the streaming instability (Kulsrud & Pearce 1969; Wentzel 1974). The phase velocity of the waves in question (e.g. fast or Alfvén waves) is much smaller than the speed of light, the velocity at which the CRs propagate. Thus, a CR perceives a packet of magnetic disturbances as stationary in time, but not space (Kulsrud 2005). Therefore the appropriate resonance condition for the interaction between a CR beam centered in energy at some Lorentz factor $\gamma$ and a wave packet of magnetic disturbances of some width $\Delta k$ is that the Larmor radius of the CRs equal to the component of the wavelength projected along the laminar field.

The growth time of the streaming instability is ex-
tremely short in comparison to local dynamical times of interstellar matter for 1-10 GeV CRs. In the absence of damping CRs excite waves which propagate along the background field with a growth rate proportional to the ratio of the streaming or diffusion velocity to the Alfvén speed $v_D/v_A$. As the amplitude of the waves grows, forward momentum is extracted from the streaming CRs as they are isotropized, while simultaneously reducing their streaming velocity. Wave excitation continues until $v_D \approx v_A$, where the instability is quenched and the instability’s source of free energy has been removed.

Now, we may write the CR optical depth as

$$\tau_{\text{CR}} \simeq \frac{c}{v_A}. \quad (28)$$

From this, the CR optical depth of the Milky Way halo with $v_A \sim 150 \text{ km s}^{-1}$ is $\tau_{\text{CR}} \sim 2 \times 10^3$, which is roughly the observed value.

In order for the streaming instability to operate at given resonant wavelength, the growth rate of the instability must surpass the individual damping rates resulting from all sources of dissipation, such as ion-neutral drag. The growth rate due to the streaming instability for a given resonant Alfvén wave is proportional to the number density of CRs $n(E)$ resonant with the magnetic disturbance in question. Due to the steepness of the CR energy spectrum, the CR number density at 100 GeV $n(E = 100 \text{ GeV})$ is sufficiently low that driving resulting from the streaming of CRs cannot overcome ion-neutral drag (Cesarky 1980). The argument presented above represents a major shortcoming of the “self-confinement” picture of CR transport.

3.2.2. Kolmogorov Cascade

On its own, the interstellar gas may be a rich source of small scale resonant Alfvénic disturbances. In this case, the CR mean free path $\lambda_{\text{CR}}$ is limited by the amplitude of magnetic fluctuations on the Larmor scale.

In the frame of the CR beam, magnetic irregularities of the interstellar medium are effectively stationary and thus, diffusion occurs only in space since energy is roughly conserved per scattering event. Spatial diffusion proceeds in pitch-angle with disturbances that are resonant with the individual CRs in momentum-space. The appropriate diffusion coefficient $D_{\text{CR}}$ is roughly given by

$$D_{\text{CR}} \simeq c r_L \frac{B^2}{\delta B^2 (r_L)}. \quad (29)$$

Here, $\delta B (r_L)$ is the amplitude of magnetic fluctuations on the Larmor scale. If the magnetic fluctuations follow a Kolmogorov scaling, then $\delta B = \delta B_0 (\lambda/\lambda_0)^{1/3}$, where $\lambda$, $\lambda_0$, and $\delta B_0$ is the eddy scale, the stirring scale, and the magnetic fluctuation amplitude at the stirring scale.

The above expression reflects the notion that a given CR can only wander in pitch-angle of its guiding center with the aid of resonant magnetic irregularities. Since the phase of the irregularities are taken as random, a CR must execute $B^2/\delta B^2 (r_L)$ gyrations before its net trajectory, and thus momentum, is altered at the order unity level. It follows that the CR mean free path $\lambda_{\text{CR}} \simeq D_{\text{CR}}/c$, when the source of magnetic deformations is due to turbulence. With this, the CR optical depth in the presence of resonant Kolmogorov magnetic turbulence reads

$$\tau_{\text{CR}} \simeq \frac{H/\lambda_{\text{CR}}}{c} \sim c H/D_{\text{CR}}$$

$$\tau_{\text{CR}} \simeq \frac{\xi_B}{r_L} \left( \frac{H}{\lambda_0} \right)^{1/3} \left( \frac{H}{\lambda_0} \right)^{2/3} \quad (30)$$

where $\xi_B = \delta B_0/B$.

As previously mentioned, the Alfvénic cascade must possess, with sufficient amplitude, eddies that are resonant with the CRs at the Larmor scale. In order to be resonant, the Alfvén waves should propagate primarily along the field. However, it is now generally accepted that, in accordance with Goldreich, Sridhar and Lithwick’s (Goldreich & Sridhar 1995; Lithwick & Goldreich 2001) theory of interstellar MHD turbulence, Alfvénic power flows only into eddies that propagate in the direction perpendicular to the large scale field. Thus, for $\lambda_0/r_L \gg 1$, there may be virtually no resonant turbulent power left at the Larmor scale.

3.3. Cosmic Ray Destruction

Cosmic rays can be destroyed once they interact with an ambient proton, subsequently producing pions. At a few GeV, the cross section for this inelastic process is $\sim 30 \text{ mb}$. Therefore, the characteristic destruction time $t_\pi$ for GeV CR protons is (Schlickeiser 2002)

$$t_\pi \simeq \frac{10^8}{n_H} \text{ yrs}, \quad (31)$$

which should be compared to the diffusion (or escape) time over a galactic scale height $H$ that is occupied with gas of average density $n_H$.

In the Milky Way, the destruction timescale $t_\pi$ does not play an appreciable role in the transport of CR protons. Note that this statement is independent on whether or not the one-zone or disk + halo model is utilized to interpret grammage measurements since the hydrogen number density throughout the Milky Way is relatively low.

In young bright starbursting galaxies $n_H$ may reach values of $10^3 - 10^4 \text{ cm}^{-3}$, corresponding to a destruction time of $t_\pi \sim 10^5 - 10^4 \text{ yrs}$. It follows that in some of the interesting cases in which CR feedback might be important, CRs may in fact be destroyed before they traverse a galactic scale height. In this case, an effective optical depth must be employed when diagnosing the level of feedback that CRs exert back upon the interstellar medium. If a CR is destroyed before it escapes the galaxy, it still has the the opportunity to exchange momentum with a given galaxy’s gaseous component. We define the effective CR optical depth, $\tau_{\text{CR}}$, as

$$\tau_{\text{CR}} = \tau_{\text{CR}} \sqrt{\frac{t_\pi}{t_{\text{diff}}}} = \sqrt{\frac{\tau_{\text{CR}}}{\tau_\pi}}, \quad (32)$$

where $\tau_{\text{CR}} \sim H/\lambda_{\text{CR}}$, $t_{\text{diff}}$ is the diffusion time for the CR protons over the galactic scale height $H$, and $\tau_\pi$ is CR the absorption optical depth to pion production.

The above expression acknowledges the fact that CRs must scatter $\tau_{\text{CR}}^2$ times in order to traverse a distance $H$ in a diffusion time $t_{\text{diff}}$. In the limit that $t_\pi < t_{\text{diff}}$, the square of the effective optical depth $\tau_{\text{CR}}^2$ is equal to the number of times a CR proton scatters and exchanges momentum with the galaxy before its destruction.

Perhaps in the most extreme cases, destruction of CR protons due to pion production will inhibit the efficiency...
of CR feedback. Consider the example of a gas-rich disk with $n_H \sim 10^{4} \text{ cm}^{-3}$ and a disk scale height $H \sim 100$ pc. The destruction timescale $t_s \sim 10^{4}$ yrs is quite short. If $\tau_{\text{CR}} \sim 10^{3}$ for this 100 pc disk then $\lambda_{\text{CR}} \sim 0.1$ pc and $t_{\text{diff}} \sim 3 \times 10^{5}$ yrs. Therefore, $\tau_{\text{CR}} \sim 0.2 \tau_{\text{CR}} \sim 200$ – a significant reduction, but not a catastrophic one.

For galactic environments in which 1-10 GeV CRs are destroyed by hadronic processes before their escape eq. [32] provides a prescription for estimating the effective CR pressure $\overline{P}_{\text{CR}}$ given by

$$\overline{P}_{\text{CR}} = F_{\text{CR}} \tau_{\text{CR}} = F_{\text{CR}} \tau_{\text{CR}} \sqrt{\frac{t_{\pi}}{t_{\text{diff}}}}. \tag{33}$$

In their eq. (44), Jubelgas et al. (2006) formulate that the effective CR pressure $\overline{P}_{\text{CR}} \propto t_{\pi}$, rather than $\overline{P}_{\text{CR}} \propto t_{\pi}^{1/2}$. The net effect is a sharp reduction in $\overline{P}_{\text{CR}}$ with $t_{\pi}$ and consequently $n_H$ since $t_{\pi} \propto n_H^{-1}$. This would be the case if either $\tau_{\pi} > \tau_{\text{CR}}$ and/or $\tau_{\text{CR}} \leq 1$. However, for almost any imaginable galactic environment, $\tau_{\pi} \ll \tau_{\text{CR}}$ and $\tau_{\text{CR}} \gg 1$.

In extreme situations were the CR mean free path $\lambda_{\text{CR}}$ is small and the hydrogen number density $n_H$ is high, 1-10 GeV CRs may never escape the galaxy as meson destruction will destroy them. The net displacement a CR may never escape the galaxy as meson destruction will destroy them. The net displacement an $\lambda_{\text{CR}}$ and low end $n_H$ is high, 1-10 GeV CRs may never escape the galaxy as meson destruction will destroy them. The net displacement $l_{\text{CR}}$ is given by $l_{\text{CR}} \simeq \lambda_{\text{CR}} N_s^{1/2}$, where $N_s = t_{s}/t_{\pi}$ is the number of scatterings before destruction and $t_{s} = \lambda_{\text{CR}}/c$ is the time in between scattering events. For typically extreme galactic parameters,

$$l_{\text{CR}} \simeq 50 \left( \frac{\lambda_{\text{CR}}}{0.1 \text{ pc}} \right)^{1/2} \left( \frac{10^{4} \text{ cm}^{-3}}{n_H} \right)^{1/2} \text{ pc}. \tag{34}$$

Clearly, for values at the high end of $n_H$ and low end of $\lambda_{\text{CR}}$, the destruction length $l_{\text{CR}}$ approaches the scale height of the starburster. If in fact this is the case, then most likely a CR feedback scenario will run into some of the same problems photon-driven feedback suffers from as mentioned in Appendix B. Though the destruction rate increases with decreasing density, the characteristic size of the starbursters also decreases with increasing density, and thus both effects have a tendency to cancel.

### 3.4. Overall Picture and Summary

If in fact the expulsion of CRs is the mechanism responsible for limiting the luminosity of starbursting galaxies, then the CRs must be well-coupled to the interstellar gas such that the CR optical depth $\tau_{\text{CR}}$ is large. Of course, there are direct measurements of CR properties in other galaxies, which is why we have utilized observations and theories of the CR transport in the Milky Way as our benchmark. Even for the Milky Way, the value of the CR mean free path $\lambda_{\text{CR}}$ extracted from the data may vary by an order of magnitude, where $\lambda_{\text{CR}} \sim 1$ pc if the halo model is utilized and $\lambda_{\text{CR}} \sim 0.1$ pc for the leaky box interpretation.

From the theoretical side, the two most commonly accepted explanations for the source of small scale resonant magnetic fluctuations possess severe weaknesses. Since the growth rate of the streaming instability at a given CR energy is proportional to $n(E) \propto E^{-2.7}$, the streaming instability is not strong enough to overcome ion-neutral damping at energies above 100 GeV (Cesarsky 1980). Perhaps one might account for the lack of an-isotropy – and thus small mean free path – above 100 GeV asserting that the source or magnetic irregularities on those scales comes about from a turbulent cascade of resonant magnetic power. However, it seems unlikely that the slope of the CR distribution function with energy remains constant over ~ 6 decades in energy if the streaming instability were to inject power at energies below ~ 100 GeV.

Despite these disturbing inconsistencies in the overall picture of CR transport in the Milky Way, what we know for certain is that the scattering optical depth $\tau_{\pi}$ is large such that $\tau_{\pi} \sim 10^{3} - 10^{4}$. Furthermore, we may conclude, with an acceptable degree of confidence, that the origin of the small CR mean free path $\lambda_{\text{CR}} \sim 0.1 - 1$ pc in the Milky Way is magnetic in nature. Within the context of galaxy formation, the fundamental issue is constraining how $\tau_{\text{CR}}$ and $\lambda_{\text{CR}}$ evolves with environment (redshift and halo mass). In what follows, we briefly discuss the manner in which $\tau_{\text{CR}}$ might evolve from galaxy to galaxy.


Eq. (35) appears strikingly similar to Faber-Jackson (1976) relation. Under the plausible assumption that galaxies residing on the Faber-Jackson relation are faded and elderly versions of their former starbursting past, then a momentum-driven feedback mechanism may indeed lead to the Faber-Jackson relation. If CR feedback is responsible for the relation, then the CR optical depth $\tau_{\text{CR}}$ can only evolve weakly with velocity dispersion $\sigma$.

The CR optical depth $\tau_{\text{CR}}$ depends on galactic magnetic field strength if either the streaming instability or a Kolmogorov cascade is responsible for the required resonant magnetic fluctuations. The situation is more complicated in the case where a magnetic cascade is responsible for the CR optical depth since knowledge of $B, \lambda_0$ and the power law index of the cascade is required as well. At the moment, a first principles calculation of $\tau_{\text{CR}}$ in the Milky Way would be a difficult task for reasons already mentioned. Certainly, an attempt to determine $\tau_{\text{CR}}$ from basic physical argument in other galaxies is out of reach.

As stated in §3.4.1, $\tau_{\text{CR}}$ cannot assume and indefinitely high value. In other words, only a finite number number of scatterings are required before the CR beam vanishes due to adiabatic losses and thus, energy conservation enforces an upper limit on $\tau_{\text{CR}}$. Furthermore, if the CR residence time, and consequently $\tau_{\text{CR}}$, becomes too large then meson production will limit the effective optical depth $\overline{P}_{\text{CR}}$ to a moderate value. Note that the $\tau_{\text{CR}}$ is bounded from above as a result of constraints that have nothing to do with the ultimate – and highly uncertain – mechanism that generates the required resonant Alfvènic disturbances that ends up scattering the CRs.

On less solid grounds, we can conclude that $\tau_{\text{CR}}$ cannot take on values that are too low for a given galaxy. If the galactic magnetic field is too weak, then the growth rate of the streaming instability is enormous since the ratio $c/v_A$ becomes very large. On the other hand, if the galactic field is quite strong on the stirring scale, then one would expect that the amount of resonant power at $v_L$ is quite large, leading to a relatively small mean free path.
Cosmic Ray Feedback

From the process of star formation, cosmic rays represent only a minor form of energy release. Yet, their momentum coupling with the interstellar medium is absolute as result of their small scattering length. As long as the CR mean free path $\lambda_{\text{cr}}$ does not greatly differ from the inferred value in the Milky Way, the collective force that CRs exert upon the interstellar medium as they leak out is great enough to support the gaseous component against gravity and may even unbind it.

If CR feedback is an important mechanism in determining the maximum luminosity of a starbursting galaxy, then the CR optical $\tau_{\text{cr}}$ must be large in order to compensate for the relatively small CR luminosity. Consequently, galactic CRs necessarily impart momentum upon the interstellar medium in the direction opposite to the galaxy’s gravitational center implying. Thus, CR feedback is highly independent of the spatial distribution of CR injection sites such as SNe and stellar winds.

In analogy with the photon-driven winds of massive and asymptotic giant branch stars, CR-driven galactic winds may reach terminal velocities in excess of the escape velocity by a factor of $\sim$ a few. Due to multiple scatterings in the galactic halo, above the main body of the galaxy, the CR beam may indefinitely accelerate a parcel of fluid up to the point where all of the CRs are redshifted away.

The main uncertainty in the CR feedback theory presented here is in determining the manner in which the CR mean free path $\lambda_{\text{cr}}$ (or optical depth $\tau_{\text{cr}}$) and radiative efficiency $\epsilon_{\text{cr}}$ varies from galaxy to galaxy. The optical depth $\tau_{\text{cr}}$ cannot approach arbitrarily high values since adiabatic losses and meson production will eventually remove energy out of the CR beam.

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APPENDIX

APPENDIX A: A GALAXY AS AN ISOTHERMAL SPHERE

As a baseline model, we assume the mass profile of a given galaxy is that of a singular isothermal sphere. This assumption is more accurate for hot systems such as elliptical galaxies and bulges and less accurate for disk galaxies. The density profile of the gaseous component is given by

$$\rho(r) = \frac{f_g \sigma^2}{2\pi G r^2},$$  \hspace{1cm} (A1)

which corresponds to an enclosed gas mass of

$$M_g(r) = \frac{2f_g \sigma^2 r}{G}.$$  \hspace{1cm} (A2)

In the above expressions, $f_g$, $\sigma$, and $r$ are the gas fraction, velocity dispersion, and galactic radius, respectively.

APPENDIX B: BREAKDOWN OF THE ONE-ZONE MODEL FOR RADIATIVE FEEDBACK

We assume that every massive star is embedded such that every single one of its emitted UV photons are absorbed by dust grains and reprocessed into infrared radiation close to the star. This is not the case in the Milky Way where massive stars are embedded for only $\sim 10\%$ of their lifetimes (Wood & Churchwell 1989). However, for starbursting sources, the ratio of infrared to UV radiation is large, implying that our assertion of every massive star being embedded is correct.

UV photon power is converted into the IR at a characteristic radius of $\sim 0.1 \text{–} 1 \text{pc}$ from the center of each individual star. It is in this region, the so-called “cocoon,” in which momentum is directly exchanged between light and matter. Note that the characteristic hydrogen number densities in this region range from $n \sim 10^3 \text{–} 10^7 \text{ cm}^{-3}$ (Koo & Kim 2001; Churchwell 2002).

There are $\sim 10^4$ O stars in the Milky Way. For a starburst galaxy with $n_{\text{gas}} \sim 100$ or so times the Milky way value, one expects there to be $N_{\text{O}} \sim 10^6$ or so massive stars responsible for both the starburst luminosity as well as the injection of radiation momentum. If the volume of this galaxy is $\sim 10^9 \text{ pc}^3$, then the typical separation between each O star is $\Delta x \sim (V/N_{\text{O}})^{1/3} \sim 10 \text{ pc}$ for a homogeneous and spherically symmetric distribution of O stars.

Furthermore, the photons from each O star may be thought of as being responsible for injecting momentum into $1/N_{\text{O}}$ of the given galaxy’s gaseous component. It follows, that momentum balance for a parcel of dusty gas placed somewhere between two typical massive stars may be expressed as

$$\rho \frac{\kappa_{\text{UV}}}{c} \frac{L_{\text{O}}}{{4\pi} \Delta x^2} \sim \rho \frac{v^2}{\Delta x/2},$$  \hspace{1cm} (B1)

where $\kappa_{\text{UV}}$ and $L_{\text{O}}$ is UV opacity on dust and the characteristic luminosity of an O star. In the above expression, the radiation force imparted at the surface of the dusty “cocoon” is matched by a non-linear momentum sink, which can be thought of as either an outward moving shell or a parsec-scale turbulent eddy. Integrating over the volume in between the two stars gives

$$\frac{L_{\text{O}}}{c} \tau \sim M \frac{v^2}{\Delta x/2},$$  \hspace{1cm} (B2)
where \( M_\Delta \sim f_g M(R)/N_{O_*} \) is the fraction of gaseous galactic mass in which a given massive star is responsible for accelerating. Noting that \( L_{O*} = L_{SF}/N_{O_*} \) together with the “single scattering approximation” (\( \tau = 1 \)) of MQT, we may write

\[
v^2 \sim \frac{L_{SF} G}{2 c f_g \sigma^2} \left( \frac{\Delta x}{2} \right).
\] (B3)

For \( L_{SF} = L_M \), where \( L_M = 4 f_g c \sigma^4/G \) is maximum stellar luminosity derived in MQT, we find that

\[
v \sim \sigma \sqrt{\frac{\Delta x}{R}} \sim \sigma N_{O_*}^{-1/6}.
\] (B4)

For a bright starburst galaxy with \( N_{O_*} \sim 10^6 \), the radiation force may lead to random fluid motions in the gas with characteristic velocities of only \( \sim 1/10 \) that of the isothermal velocity dispersion. Therefore, it seems highly unlikely that radiation-driven feedback can lead to the unbinding of a galaxy’s gaseous component. The clustering of massive stars won’t alleviate this major concern with respect to radiation feedback. Even if O stars are embedded together 100 at a time behind a common dust sublimation layer, the random velocity \( v \) increases by only a factor of \( \sim 2 \).

APPENDIX C: MOMENTUM AND ENERGY CONSERVATION FOR OPTICALLY THICK RADIATION-DRIVEN WINDS

Here, CRs are taken to provide the radiation pressure that ultimately drives out a given galaxy’s gaseous component. By making the simplifying assumption that the force exerted by the CRs upon the gas greatly exceeds the gravitational and thermal pressure forces, the luminosity in CRs may be related to the outgoing momentum of the wind by

\[
\dot{P}_w = \dot{M} v_w = \frac{L_{CR}}{c} \tau,
\] (C1)

where \( P_w, \dot{M}, \) and \( v_w \) is the momentum, mass loss rate, and terminal velocity of the wind, respectively (Lamers & Cassinelli 1999). In eq. (C1), the optical depth of the wind \( \tau \) cannot be arbitrarily large and is constrained by energy conservation of the flow i.e.,

\[
L_{CR} \leq \frac{1}{2} \dot{M} v_w^2.
\] (C2)

It follows that \( \dot{M} v_w \leq 2 L_{CR}/v_w \), which gives an upper limit for the optical depth

\[
\tau \leq \frac{2c}{v_w}.
\] (C3)

In the extreme limit, where \( \tau = 2c/v_w \), are completely redshifted away due to adiabatic expansion since they have transferred all of their energy to the matter.

APPENDIX D: TURBULENT POWER OF MOLECULAR CLOUDS REGULATED BY COSMIC RAYS

The observation that the light to mass ratio \( R \) of both “fully populated” molecular clouds and bright dense regions of starbursting galaxies are equal imply the presence of a common feedback mechanism. Here, we explore the possibility of whether or not the production and transport of CRs within giant molecular clouds (GMCs) can regulate star formation.

In the Galaxy, their is \( \sim 10^9 M_\odot \) of molecular gas responsible for the formation of stars and most of this mass is in the form of GMCs (Binney & Tremaine 1987). We work under the assumption that turbulence is dominant form of pressure support and that the molecular cloud is in virial balance.

The amount of power or luminosity required to maintain steady turbulence in a GMC, \( L_{turb} \), may be expressed in terms of \( M_c, v_c \), and \( \Delta t_{turb} \), which represent the mass of the GMC, the turbulent velocity of the outer scale \( l_c \), and the eddy turnover time on the outer scale, respectively. We have

\[
L_{turb} \sim M_c \frac{v_c^2}{\Delta t_{turb}} \sim M_c \frac{v_c^3}{l_c} \sim 2 \times 10^{36} M_6 v_3^3 l_{10}^{-1} \text{ erg s}^{-1},
\] (D1)

where \( \Delta t_{turb} \sim l_c/v_c \) and \( M_6, v_3 \) and \( l_{10} \) is \( M_c \) in units of \( 10^6 M_\odot \), \( l_c \) in units of 10 pc, \( v_c \) in units of 3 kmps\(^{-1} \), respectively.

Now, we estimate an upper limit for the amount of power in CRs, which may be injected into the GMC. As usual, the source of CR power is assumed to be core-collapse SNe and well as winds from massive stars. Again, we take into account that massive stars are embedded i.e., in physical contact with their natal GMC, for only \( \sim 10 - 20\% \) of it’s life (Wood & Churchwell 1989). From this, we infer that a similar fraction of the SNe and stellar wind power comes into contact with its ancestral GMC. Putting this together, the CR energy injection rate that a GMC is subject reads

\[
L_{CR}^\text{cloud} \sim \xi \frac{M_c}{M_{mol}} L_{CR} \sim 6 \times 10^{36} \xi_{0.1} M_6 M_{mol}^{-1} \epsilon_6 \dot{n}_{\text{w,b}} \text{ erg s}^{-1}.
\] (D2)
Here $\xi$ and $M_{\text{mol}}$ represent the fraction of massive stars that reside within their parent GMC at any given time and the entire molecular mass content of the Galaxy and furthermore, $M_{\text{mol},9}$ and $\xi_{0.1}$ are $M_{\text{mol}}$ and $\xi$ in units of $10^9 M_\odot$ and 0.1, respectively.

On energetic grounds, the above expressions indicate that CRs indeed may be a crucial agent of self-regulation for GMCs.

REFERENCES

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