DUST-DRIVEN WIND FROM DISK GALAXIES

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ABSTRACT

We study gaseous outflows from disk galaxies driven by radiation pressure on dust grains. We include the effect of bulge and dark matter halo and show that the existence of such an outflow implies a maximum value of disk mass-to-light ratio. We show that the terminal wind speed is proportional to the disk rotation speed in the limit of a cold gaseous outflow, and that in general there is a contribution from the gas sound speed. Using the mean opacity of dust grains and the evolution of the luminosity of a simple stellar population, we then show that the ratio of the wind terminal speed ($v_\infty$) to the galaxy rotation speed ($v_r$) ranges between 2 and 3 for a period of $\sim$10 Myr after a burst of star formation, after which it rapidly decays. This result is independent of any free parameter and depends only on the luminosity of the stellar population and the relation between disk and dark matter halo parameters. We briefly discuss the possible implications of our results.

Key words: galaxies: evolution -- galaxies: starburst -- intergalactic medium

1. INTRODUCTION

Galactic outflows are believed to be an important ingredient in the evolution of galaxies. It is thought to provide a feedback mechanism for the regulation of star formation in galaxies, and the subsequent chemical evolution in them. Also, galactic scale winds are thought to enrich the intergalactic medium (IGM) with metals. Observations also show that galactic scale outflows are common in starburst galaxies in both the local and high-redshift universe (Veilleux et al. 2005).

In the standard scenario, the interstellar medium (ISM) of the starburst galaxy is heated by supernovae (SNe) and the thermal pressure of the hot gas drives the outflowing gas. Larson (1974), Saito (1979), and Dekel & Silk (1986) argued that SNe in a star-forming galaxy would drive an outflow in excess of the escape speed from the galaxy. This scenario, however, has met with problems from new observations. Recent observations of cold clouds embedded in the hot gas show that the maximum speed of these clouds is correlated with the star formation rate (SFR, Martin 2005), a correlation that is more easily explained by outflows driven by radiation pressure than thermal pressure. Observations of Lyman break galaxies at $z \sim 3$ have also found a correlation between the outflow speed and the SFR, as well as with the reddening due to dust. Also, SN explosions in disk galaxies may only produce a thickening of the disk gas because of the incoherent nature of these explosions (Fragile et al. 2004). Moreover, cold clouds embedded in the hot gas in the outflow are not likely to survive longer than a Myr because of various instabilities and/or evaporation by thermal conduction.

Murray et al. (2005), hereafter referred to as MQT05) showed that radiation pressure can be comparable to the ram pressure in high outflows, and considered radiatively driven shells of gas and dust. Martin (2005) found that this scenario provides a better framework in order to understand the observed correlations. Nath & Silk (2009) discussed a hybrid model of outflows with radiation and thermal pressure.

In this Letter, we study dust-driven gaseous winds from luminous disk galaxies. We estimate the terminal speed of the combined gas and dust flow, taking into account the gravity of the dark matter halo and the disk mass-to-light ratio that is expected from stellar population synthesis models.

2. DUST-DRIVEN WIND FROM A KEPLERIAN DISK

Recently, Zhang & Thompson (2010) considered a disk of radius $d$, constant surface density ($\Sigma$), and surface brightness $(I)$. Assuming a cylindrical geometry, the force of gravitation $f_g(z)$ and that due to radiation $f_r(z)$ along the pole are given by

$$f_g = \frac{2\pi \kappa I}{c} \int \frac{z^2 r dr}{(r^2 + z^2)^{3/2}},$$

$$f_r = \frac{2\pi \kappa I}{c} \int \frac{z^2 r dr}{(r^2 + z^2)^{3/2}},$$

where $\kappa$ is the average opacity of dust grains to absorption and scattering of photons. The ratio of these forces, the Eddington ratio, increases with height $z$, beginning with a value of $\Gamma_0 = \frac{\sqrt{2}}{\pi\kappa I}$ at the disk center at $z = 0$. From energy conservation they found the velocity at height $z$ to be

$$v_z^2 = 4\pi G \Sigma d \left( \frac{z}{d_0} \right) - 1 - \frac{z}{d_0} + \sqrt{1 + \frac{z^2}{d_0^2}}.$$  

This implies a terminal velocity of $v_\infty \sim 4\sqrt{\pi G \Sigma d (\pi \Gamma_0/2 - 1)}$, with a lower limit on $\Gamma_0 \sim 2/\pi$ for driving an outflow.

Assuming a Keplerian disk with average rotation speed of $v_{c,\text{kep}} \sim \sqrt{\frac{\pi G \Sigma d}{\pi \Gamma_0}}$, the terminal velocity can be written as $v_\infty = 4\sqrt{\frac{\pi G \Sigma d}{\pi \Gamma_0}} (v_{c,\text{kep}})$, which yields a value $v_\infty \simeq 3(v_{c,\text{kep}})$ for $\Gamma_0 = 1$. But these results will change with the proper inclusion of bulge and dark matter halo.

3. GASEOUS OUTFLOWS

In this Letter, we discuss steady, rotating wind in which dust is propelled outward by radiation pressure and drags the gas with it. We ignore magnetic forces and treat the wind as a single-phase fluid, which is marginally optically thick (MQT05).

Although our results are valid for all temperatures, in practice the model allows for only cold flows (as observed in Na i and Mg ii lines; e.g., Martin 2005) for the following reasons. The sputtering radius for grains over a wind timescale of 10 Myr (which we derive below) is $a \sim 50 \times \frac{a_{\text{dust}}}{\zeta_{\text{dust}}} \AA$ for $T \sim 10^5$ K (Tielens et al. 1994), which implies that only grains smaller than 5 Å are destroyed, without changing the
opacity. But the radiative-cooling time is small (≤1 Myr), so for adiabatic approximation to be valid, the adiabatic-cooling timescale should be shorter than the radiative-cooling timescale, which limits the temperature to ≤10⁴ K. Also the timescale for dust heating is ~10 Myr and can be neglected.

Second, we improve upon the previous estimates of the required value of \( \Gamma_0 \) needed to drive a wind by taking into account the gravity of bulge and halo. Clearly, the relation between \( v_\infty \) of the wind and \( v_c \) in which the rotation speed is estimated from a Keplerian disk is not relevant for disk galaxies because the rotation speed must be calculated from the dark matter halo.

### 3.1. Disk, Bulge, and Halo Parameters

We consider a disk with constant surface density (\( \Sigma \)) and surface brightness (\( I \)), of radius \( d \), and which is embedded in a bulge and a halo. We assume a spherical mass distribution in the bulge and the halo. For the bulge, we assume a total mass of \( M_b \) inside a radius \( r_b \ll d \).

For the halo, we consider a Navarro–Frenk–White (NFW) profile with total mass \( M_d \) characterized by a concentration parameter \( c = r_{200}/r_s \) (Navarro et al. 1997). We fix the total halo mass for a given disk mass (\( M_d = \pi d^2 \Sigma \)) by the ratio \( M_b/M_d \approx 1/0.05 \) as determined by Mo et al. (1998, referred to as MMW98 hereafter). We use the prescription of MMW98 for the disk exponential scale length \( R_d \sim (1/\sqrt{2})\lambda_d R_{200} \), using their Equations (23), (26), and (32), and use \( d = R_d/\sqrt{2} \), since the total masses in the case of uniform density and exponential disk are given by \( M = \pi d^2 \Sigma = 2\pi d \Sigma R_d^2 \).

The rotation speed implied by the NFW profile peaks at a radius \( r \sim 2r_s \), given by

\[
v_c^2 = v_{200}^2 \frac{c}{2} \frac{\ln(3) - 2/3}{\ln(1 + c) - c/(1 + c)},
\]

where \( r_s \) is the scale radius of the NFW profile and \( v_{200} \) is the rotation speed at the virial radius. We choose this value of the maximum rotation speed to represent \( v_c \) of the disk galaxy, since Figure 2 of MMW98 shows that the value of \( v_c \) from the flat part of the total rotation curve does not differ much from the peak of the rotation curve from the halo only. We also use \( r_b/d \sim 0.1 \) and \( M_b/M_d \sim 0.5 \), consistent with the observed range of luminosity ratio between a bulge and a disk (Binney & Merrifield 1998, p. 220).

### 3.2. Wind Terminal Speed

To determine the terminal speed of the wind, we use the fact that the Bernoulli function is preserved along a streamline, assuming that a streamline extends from the base to infinity. In an isothermal wind, the terminal speed tends to infinity as the wind maintains a constant sound speed. It is however more reasonable to assume a polytropic equation of state.

One can write the Bernoulli equation for a polytropic gas (with an adiabatic index \( \gamma \)) along a streamline: \( \frac{v^2}{2} + \frac{c^2}{\gamma - 1} + \phi = E \), where \( c \) is the sound speed, \( \phi \) is the potential, and \( E \) is a constant. Equating the values at the base and infinity, we have

\[
\frac{v_c^2}{2} + \frac{c_{s,\infty}^2}{\gamma - 1} + \phi_\infty = \frac{v_\infty^2}{2} + \frac{c_{s,b}^2}{\gamma - 1} + \phi_b,
\]

where \( v_\infty \) is the wind speed at the base (\( z = 0 \)), \( c_{s,b} \) is the sound speed at the base, and \( c_{s,\infty} \) is the sound speed at infinity, which is negligible. The potential is

\[
\phi = -2\pi G \Sigma d \Gamma_0 \tan^{-1}(z/d) + 2\pi G \Sigma d \left( \frac{z}{d} - \sqrt{1 + \frac{z^2}{d^2}} \right)
\]

\[
+ \frac{L^2}{2v_c^2} - \frac{GM_b}{\sqrt{r^2 + z^2}} - \frac{GM_b \ln(1 + r/r_s)}{r/r_s}.
\]

Here the first term denotes a pseudo-potential due to radiation pressure. The second term refers to the gravitational potential of the disk, and here we have assumed for analytical simplicity that gas stays near the pole, so these forces are given by Equation (1). The third term is the potential due to the centripetal force of the rotating gas in the wind and the last two terms denote the effect of the bulge and halo gravity. We also assume that the bulge exerts a negligible radiation pressure, since the dominant bulge stellar population is old and red and the mean opacity \( \kappa \) of dust grains in these wavelengths is smaller than in the blue band.

The centrifugal force at the base of the rotating wind should be equal to the gravitational force due to the mass inside \( a \), the radial distance at the base. We assume that \( a \gg r_b \), the bulge radius, while being much smaller than \( d \), the disk radius. Hence the centrifugal force is written as

\[
\frac{L^2_{\text{base}}}{a^3} = \frac{GM_b}{a^2} + \frac{GM_d}{a^2} \left[ \ln \left( 1 + \frac{a}{r_s} \right) - \frac{a}{a + r_s} \right].
\]

The first term on the right-hand side is due to the bulge and the second term is due to the dark matter halo. For \( a \ll r_s \), the second term can be approximated as \( \frac{GM_d}{a^2} \), which is much smaller than the bulge term \( \frac{GM_b}{a^2} \), because the gravity of baryons dominates at small radii. Neglecting the halo term, the specific angular momentum is given by

\[
L_{\text{base}} = \sqrt{GM_b a}.
\]

Finally, the values of the potential at the base and infinity are as follows:

\[
\phi_b = -2\pi G \Sigma d + \frac{GM_b}{2a} - \frac{GM_b}{a} - \frac{GM_d}{r_s} \left[ \ln(1 + a/r_s) - \frac{a}{a + r_s} \right]
\]

\[
\phi_\infty = -2\pi G \Sigma d \left( \frac{\Gamma_0 \pi}{2} \right).
\]

We note that the radiation pseudo-potential is zero at the base but is \( -2\pi G \Sigma d (\Gamma_0 \pi) \) at infinity along the pole. Since the dark matter halo is truncated at \( r_{200} \), its potential vanishes at infinity.

It is reasonable to assume that the wind speed at the base is comparable to the sound speed in the disk (\( v_b \sim c_{s,b} \)). Putting it all in Equation (4), we have the following expression for the terminal speed:

\[
v_\infty^2 = \frac{\gamma + 1}{\gamma - 1} c_{s,b}^2 + 2\pi G \Gamma_0 \frac{GM_d}{d}
\]

\[
- \frac{[4GM_b + GM_d + 2GM_d \ln(1 + a/r_s)]}{a}.
\]

We emphasize that \( \Gamma_0 \) refers only to disk parameters and \( \Gamma_0 = 1 \) does not signify Eddington luminosity for radiation pressure on dust.
Figure 1. Ratio between \( v_\infty \) and \( v_c \) shown as a function of \( \Gamma_0 \) for galaxies with two different concentration parameters \( c \), for cold gaseous outflow.

Figure 2. Ratio between \( v_\infty \) and \( v_c \) shown as a function of \( \Gamma_0 \) for galaxies with different \( v_c \) at two different redshifts.

3.3. Evolution of Wind Speed with Time

We recall that the value of \( \Gamma_0 \) depends on disk parameters (\( \Sigma, I \)) and dust grain properties (through \( \kappa \)). Consider first the value of \( \Sigma/I \) that is essentially the disk mass-to-light ratio. One can compare the observed values of mass-to-light ratio with the minimum requirement as derived above. Li & Draine (2001) give the mean opacity for gas mixed with dust as \( \sim 128 \text{ cm}^2 \text{ g}^{-1} \) in \( U \) and \( \sim 93 \text{ cm}^2 \text{ g}^{-1} \) in the \( B \) band. Here we shall consider the \( B \)-band value as a conservative estimate, which ensures that star formation is not obscured. In case of obscured star formation, shell(\( s \)) of gas and dust would be accelerated, which are likely to undergo fragmentation and produce clouds due to instabilities, facilitating the escape of ionizing photons (Razoumov & Sommer-Larsen 2010; Wise & Cen 2009).

Using \( B \)-band values, we find a maximum value of the disk mass-to-light ratio required for the outflow to occur, given by \( M/L \sim \kappa/(2\pi c G \Sigma) \). For \( c \sim 10 \), this is given by \( (M/L)_b \equiv \Upsilon_B \lesssim 0.036 \). This upper limit on disk \( \Upsilon_B \) is much lower than observed in present-day disk galaxies. The Milky Way disk has a local value of \( \Upsilon_B \sim 1.2 \pm 0.2 \) (Flynn et al. 2006), and the typical value for disk galaxies is \( 1.5 \pm 0.4 \) (Fukugita et al. 1998). According to Flynn et al. (2006), a third of the total disk mass comes from gas and the rest from stars. Starburst galaxies can have a much lower value of \( \Upsilon_B \). The estimated \( M/L_{bol} \) for NGC 7714 is \( \sim 0.02 \) (Bernlörh 1993a), for regions in NGC 520 it is \( \sim 0.003 \) (Bernlörh 1993b), and for a young super cluster in M82, Smith & Gallagher (2001) have estimated the \( \Upsilon_B \sim 0.02 \). These low values of \( \Upsilon \) are believed to arise from a top-heavy initial mass function (IMF) and young age of the stellar population (e.g., Kotilainen et al. 2001; Smith & Gallagher 2001).

For an instantaneous burst, these models predict an initial period of roughly constant luminosity for \( t \lesssim 3 \text{ Myr} \), and a decrease in the luminosity afterward (Bruzual & Charlot 2003; Buzzoni 2005; Vásquez & Leitherer 2005). For a Salpeter IMF and a stellar mass–luminosity relation of the type \( L \sim M_B^{1.35} \), the late-time decay of the luminosity is given by \( L \sim t^{-(\beta-1.35)/(\beta-1)}(\propto t^{-0.9} \text{ for } \beta = 3.5) \). The initial period of rather constant luminosity stems from the fact that while low-mass stars are yet to collapse, the massive stars evolve quickly, and the duration of this period corresponds to the main-sequence lifetime of the most massive stars.

Using these models we can determine \( \Upsilon_B \) for a stellar population, multiplying by a factor of \( \sim 3/2 \) to account for an additional gas mass, and determine the expected disk \( \Upsilon_B \) ratio as a function of time after an instantaneous starburst. Using the results in Figure 9 of Vásquez & Leitherer (2005), which uses a Salpeter IMF between 0.1 and 100 \( M_\odot \), and using \( M_{B,\odot} = 5.45 \), one can calculate \( \Upsilon_B \) as a function of time. Strength of instantaneous
starburst is characterized by the total mass converted into stars initially, which in this case is $10^6 M_\odot$.

Using the mean dust opacity for $B$ band, we calculated the time evolution of $\Gamma_0$ and then determined the wind terminal speed using Equation (9). Although the use of Equation (9) assumes a constant $\Gamma_0$ along a streamline, the distance traveled by the wind over the timescale of change of $\Gamma_0$ ($\sim 10$ Myr) is large ($t \geq 6.3 \text{kpc}(v/600 \text{ km s}^{-1})$). In other words, the timescale for the wind to reach a considerable height above the disk is comparable to the timescale of evolution in $\Gamma_0$, and therefore we can use our formalism to estimate the terminal speed with the evolution in $\Gamma_0$.

Figure 3 shows the evolution of $v_\infty/v_\star$ with time for $z = 0$ (solid line) and $z = 7$ (dotted line). The curves show that the wind speed decreases rapidly after $\sim 10$ Myr, and that $v_\infty < 3v_\star$, its value being smaller for compact galaxies. This result can be compared with the observed range of maximum wind speed. Martin (2005) found that the maximum speed of clouds embedded in outflowing gas ranges $2–3 v_\star$, and Rupke et al. (2005) found a range of $[0.67–3] v_\star$. We show this range with two dashed lines in Figure 3. Figure 3 also shows that the wind speed is somewhat smaller at high redshift. The reason is that galactic mass for a given $v_\star$ is smaller at high redshift, but $c \propto M^{-0.2} (1+z)^{-1}$, and the mass effect outweighs the redshift effect. However, the variation of $v_\infty/v_\star$ with redshift is expected to be very small in this model, much smaller than those caused by other parameters, such as the IMF.

4. DISCUSSIONS

Figure 3 shows that dust-driven winds are likely to have a terminal speed $\sim 2–3v_\star$, for a combination of reasons that involve stellar physics and the relation between disk and halo parameters. It is interesting that this result coincides with observations, since there is no free parameter in our calculation. The strength of our approach lies in the fact that the terminal speed calculated using the Bernoulli function is independent of the streamline used by the gas, as long as streamlines do extend to infinity, which is our basic assumption. Below we discuss a few implications.

In the scenario of energy-driven winds, the IGM is believed to be enriched by winds from dwarf galaxies, since they were numerous in the early universe (Silk et al. 1987; Nath & Tremonti 1997; Ferrara et al. 2000; Cen & Bryan 2001; Madau et al. 2001; Aguirre et al. 2001). However, in the case of dust-driven winds, the importance of low-mass galaxies in IGM enrichment diminishes because $v_\infty \propto v_\star$. Our calculations here show that the wind speed depends strongly on the time elapsed after a starburst, or more generally on the star formation history and parameters. It is believed that the IMF is weighted toward massive stars at high redshift (e.g., Schneider & Omukai 2010), in which case the wind speed likely increases with redshift. In this case the contribution of dwarf galaxies at high redshift may still be important.

Recent simulations for IGM enrichment including momentum-driven winds have used the ansatz $v_\infty \sim 3v_\star$ (Oppenheimer & Davé 2006), using the estimates of MQT05 for wind from a spherical galaxy radiating close to the dust Eddington luminosity. It has been suggested that the momentum-driven winds drive a feedback loop that makes $v_\infty \sim 3v_\star$ (Martin 2005; MQT05). Our calculations show that such dust-driven winds are possible only within a period of $\sim 10$ Myr after a starburst. Since the wind speed depends strongly on the value of disk $\Upsilon$, which depends on the IMF (being smaller for a top-heavy IMF), the wind speed is expected to be larger for an IMF skewed toward massive stars. The implications need to be studied with numerical simulations using modified prescriptions for the wind speed. It is possible that this puts constraints on the metallicity of the wind gas. In addition, as the dust opacity is proportional to the metallicity, $\kappa \propto Z$, the existence of a threshold $\Gamma_0$ needed for the wind to reach infinity suggests that only metal-rich galaxies can enrich IGM.

We note that our calculation does not determine streamlines, without which we cannot calculate the density structure in the wind, and therefore cannot derive the mass-loss rate. In the case of single scattering, the maximum mass-loss rate is $M \sim L/(v_\infty c)$ (MQT05). This recovers the scaling that $M \propto v_\star^{-1}$ adopted by numerical simulations (Oppenheimer & Davé 2006). Taking our results into account, the mass-loss rate for a given luminosity is expected to be lower at high redshift because of the possible rise of $v_\infty$ with $z$ arising from IMF evolution.

In summary, we have derived a terminal speed for dust-driven outflows from disk galaxies, and have shown that $v_\infty \sim (2–3)v_\star$, which is determined by the minimum value of disk $\Upsilon_g \sim 10^{-2}$ arising from the luminosity of a stellar population, and the relation between the disk and dark matter halo that fixes the terminal speed for a given value of $\Upsilon$. We have shown that dust-driven winds from disk galaxies are excited within a timescale of $\sim 10$ Myr of a starburst, after which the radiation pressure on dust is unable to drive outflows.

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