Astronomical and Astrophysical Transactions (*AApTr*), 2012, Vol. 27, Issue 2, pp. 183–186,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Radiation and thermal pressure driven galactic winds

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Received 1 February, 2012

Recent observations of outflows from galaxies do not support the standard scenario of thermal pressure driven winds. We discuss the importance of radiation pressure from massive stars in this context, and show that a hybrid model of radiation and thermal pressure driven winds may explain some key observations.

Keywords: Galactic winds; Radiation pressure; Thermal pressure

1 Introduction

Galactic outflows provide an important feedback mechanism for the evolution of galaxies. Observations have clearly shown the existence of outflows in local galaxies, and spectroscopic studies on high redshift galaxies have also found the existence of outflows in them ([1] and references therein).

These observations show that cold gas is ejected in these outflows at high speed. It is usually believed that the cold gas is embedded in a hot medium, which is produced by heating of the interstellar medium (ISM) from supernovae (SN). The standard scenario of outflows therefore posits that the thermal pressure of the hot gas drives the outflowing gas.

There are a number of problems with this scenario. Theoretically, there is the problem of the survival of this cold gas in the hot medium because of the Kelvin–Helmholtz instabilities and evaporation by thermal conduction. These processes make the survival timescale of the cold gas to be less than a Myr, whereas observations clearly show the existence of such cold gas out to several kpc. It is difficult to explain it if the wind speed is, as observed, in the range of a few hundred kilometers per second.

Also, there are a few observations which are difficult to accommodate in this standard scenario. Observations of NaI absorption lines for nearby galaxies show the existence of a correlation between the maximum speed of cold clouds and the star formation rate [2]. Observations of Lyman break galaxies (LBG) at $z \sim 3$ show that the outflow speed correlates well with the star formation rate, as well as with the reddening due to dust. In addition, the outflow speed is found to be correlated with

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the equivalent width of low ionization absorption lines. Ferrara and Ricotti [3] found that the observed correlation of outflow speed with star formation rate is difficult to explain in the standard SN-driven wind via the Sedov–Taylor phase of SN shells.

Murray et al. [4] have discussed the importance of radiation pressure which was shown to be comparable to the ram pressure of the hot outflows, and worked out the dynamics of radiatively driven shells of gas and dust. Martin [2] found that this model provides a better framework for the explanation of the correlation between maximum speed of cold clouds and the star formation rates. In this model, the star formation rate is regulated by the outflow of gas through radiation pressure.

In this context, Nath & Silk [5] presented a hybrid model of outflows with radiation and thermal pressure. In this model the radiation pressure from massive stars in a stellar population launches the cold gas surrounding the cluster to a large distance, before the massive stars explode as SNe and the ram pressure of the hot gas drives the cold clouds out of the galaxy. Murray et al. [6] have also presented a hybrid model in this context.

2 Radiation and ram pressure

Consider the effect of radiation pressure from massive stars in a stellar population of luminosity L on a shell of gas and dust at distance r. We assume that the total mass (including dark matter) contained within this distance is $M(r)$. If we denote the opacity of matter (dust plus gas) per unit mass of gas by κ (in cm^2 gm^{-1}), then the equation of motion of the shell is given by

$$\frac{dV}{dt} = -\frac{GM(r)}{r^2} + \frac{\kappa L}{4\pi r^2 c} - \frac{3V^2}{r}\,. \tag{1}$$

Nath & Silk [5] found that the shell of gas and dust moves outward and reaches a distance of a several hundred parsecs in a few Myr, for reasonable values of the dust opacity and other parameters, if the star formation rate (SFR) is large. For example, for an SFR of 100 M$_\odot$ yr^{-1}, an ambient gas density of ~ 5 particles per cc and a dust opacity of $\kappa \sim 500$ cm^2 gm^{-1}, the radiatively driven shell of gas and dust reaches a distance of roughly 1 kpc in ~ 5 Myr. This is for galaxies of total mass $M = 10^{12} M_\odot$, at $z = 3$ (assuming a Navarro–Frenk–White dark matter profile with concentration parameter $c = 3$) [7]. We have also assumed a Salpeter IMF for the stellar population. The effect of radiation pressure falls as r^{-2} with distance, and the expanding shell stalls after reaching a certain height.

The dust opacity used here is reasonable [8] for continuum absorption and scattering, and the opacity is expected to be larger at shorter wavelengths. Observations of the reddening of local and high redshift galaxies also suggest dust opacities of this order [9, 10].

We can also estimate the dust opacity from dust grains produced over a period of time in a galaxy of size r and with total gas mass $M_g(r)$, assuming a dust opacity $\tau = \kappa M_g(r)/4\pi r^2 \sim 1$. If we consider the expanding and cooling stellar ejecta in SN events as sites of dust grain production, then according to the estimates of [11–13], we typically find that dust grains of total mass $\sim M_{dust} \sim 0.5$ M$_\odot$ are synthesized per SN, with some variations due to difference in metallicity and masses of progenitor

stars. We can estimate the opacity due to dust produced over a time $t = t_9$ Gyr due to star formation rate $\dot{M}_*$, (assuming a dust-to-gas ratio of 0.01 as in our Galaxy) as

$$\kappa \sim 500\,\mathrm{cm}^2\,\mathrm{g}^{-1}\,t_9\left(\frac{\dot{M}_*}{50\,M_\odot\,\mathrm{yr}^{-1}}\right)\left(\frac{R}{5\,\mathrm{kpc}}\right)^{-2}, \tag{2}$$

where we have assumed a Type II SN rate of 7.5×10^{-3} yr $^{-1}$ for a star formation rate of $1\,M_\odot$ yr^{-1} with a Salpeter IMF, and where r denotes the size of the spherical galaxy. In other words, typical star formation rates observed in starburst galaxies, including LBGs, can give rise to $\kappa \sim 500$ cm^2 g^{-1}.

The massive stars in the stellar population would however explode within a few Myr of the formation of the population. The ejecta from these SNe would move outward in a relatively rarefied ISM, because of the effect of the radiatively driven shell that had been pushed outward previously. Assuming a gas particle density of ~ 0.01 per cc in the rarefied medium, the SN eject is likely to catch up with the radiatively driven shell and provide an added momentum to the shell.

This collision re-accelerates the shell and is likely to induce Rayleigh–Taylor (RT) instability in the shell of gas and dust. We can show that the RT instability timescale ($\tau \sim (g_{eff}k)^{-1/2}$) for the the largest wavenumber k (given by the radius of the shell), decreases and becomes comparable to the dynamical timescale of the expanding shell after the shell is re-accelerated. The effective gravitational acceleration is given by the shell speed (v) and radius (r) as $g_{eff} \sim v^2/r$. This is also likely to feed gravitational instabilities. The resulting fragments of the shell will then move outward ballistically, preserving the momentum. It is interesting to note that this is likely to happen at a distance larger than the half-light radii of LBGs, and so the clouds are likely to escape into the intergalactic medium.

Nath & Silk [5] showed that the resulting speed of the clouds correlates with the star formation rate and the correlation is a good match with the observed slope. The expected correlation between dust reddening and the outflow speed is also well matched if we assume the dust properties to be similar to the case of the Small Magellanic Cloud. The expected dust reddening in the case of Galactic and LMC-type dust grains is larger, but it is not clear how the destruction of dust in the fast moving clouds will change the reddening parameters. It is also possible that cooling behind shocks in the clouds will also produce new dust grains. One interesting possibility is that the grain size distribution in these clouds will be skewed towards small grains, because of the destruction of large grains, and the total surface area of grains will increase and the reddening for shorter wavelength ultraviolet continuum will also increase. This is likely to effect the frequency dependence in reddening which may show evolution with redshift.

3 Conclusions

Nath & Silk [5] presented a toy model for the case of a shell of dust and gas being driven by radiation pressure first and then by ram pressure of hot gas from SNe. The stellar ejecta from the massive stars moves outward in a medium rarefied by the effect of a previously expanding shell of gas and dust, by the radiation pressure of the

massive stars in the same stellar population. This ejecta collides with the radiatively driven shell and imparts renewed momentum to it. The resulting re-acceleration induces Rayleigh–Taylor instability and makes the shell unstable to fragmentation. The speed of the ballistically moving clouds is shown to be correlated with the star formation rate, in a manner shown by observations of LBGs at high redshift.

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