The Hydrodynamics and Chemical Evolution of Starburst-driven Outflows

Sergiy Silich

Instituto Nacional de Astrofísica Optica y Electrónica, Apdo. 51 y 216, 72000 Puebla, Pue. México

Guillermo Tenorio-Tagle

Instituto Nacional de Astrofísica Optica y Electrónica, Apdo. 51 y 216, 72000 Puebla, Pue. México

Abstract. The hydrodynamics and intrinsic properties of galactic-scale gaseous outflows generated by violent starbursts are thoroughly discussed, taking into account the hot gas chemical evolution and radiative cooling. We also discuss the observational properties of supergalactic winds in X-rays and visible line regimes, derived from the hydrodynamic calculations.

1. Introduction

Massive starbursts, well localized short episodes of violent star formation, are among the intrinsic characteristics of the evolution of galaxies. They are found both at high and intermediate redshifts as well as in galaxies in the Local universe.

The large kinetic luminosity produced by violent bursts of star formation is well known to drastically affect the surrounding interstellar medium (ISM), generating giant superbubbles, supershells and in extreme cases supergalactic winds. Powerful gas outflows from star forming regions are important redistributors of the ISM mass and momentum. On the other hand, the gas ejected by supernova explosions contains the products of massive stars. Therefore gaseous outflows initiated by starburst affect also the chemical evolution of the galactic ISM and the intergalactic medium.

Supergalactic winds are expected to be detectable thanks to their extended X-ray emission. Indeed, diffuse X-ray emission associated with starburst galaxies has been detected by ROSAT, ASCA, BeppoSAX, Chandra and XMM missions in several starburst sources. However, the origin of the soft X-ray emission, its connection with Hα filaments and the chemical composition of the X-ray emitting gas, remain ambiguous.

The paper deals with three central aspects of the resultant outflows. The chemical evolution expected in the interior of superbubbles. The conditions required to establish a supergalactic wind and the intrinsic properties and observational manifestations of fully developed supergalactic winds.
2. Hot gas chemical composition

The metallicity of the interstellar and intergalactic media reflects the history of star formation in the Universe. Galactic supershells and superwinds have been advocated as major mechanisms which re-distribute heavy elements throughout galactic discs and the intergalactic space. However, not until recently theoretical models did not care about the hot bubble chemical evolution and associated the hot gas metallicity with the metallicity of the surrounding ISM.

The enrichment caused by supernova products has been incorporated in the models by Silich et al. (2001). The calculations assume an instantaneous burst of star formation with a Salpeter initial mass function with an exponent $\alpha$ and incorporate the oxygen and iron yields $Y_{O,Fe}$ derived from stellar evolution models. The mass of oxygen (and iron) released by the stellar cluster of total mass $M_{SB}$ with upper and lower cutoff masses $M_{up}$ and $M_{low}$, during the evolutionary time $t$ is

$$M_{ej}(O,Fe) = \frac{(\alpha - 2)M_{SB}}{M_{low}^{2-\alpha} - M_{up}^{2-\alpha}} \int_{M_{\star}(t)}^{M_{up}} Y_{O,Fe}(m)m^{-\alpha}dm.$$  \hspace{1cm} (1)

The ejected metals were assumed to be effectively mixed with the stellar hydrogen envelopes and matter evaporated from the shock driven outer shell. The mean hot gas metallicity measured in Solar units is then

$$Z_{O,Fe} = \frac{M_{ej}(O,Fe)/Z_{\odot}(O,Fe) + Z_{ISM}M_{ev}}{M_{ev} + M_{ej}},$$  \hspace{1cm} (2)

where $Z_{\odot}(O,Fe)$ are the oxygen and iron solar content, $Z_{ISM}$ is the interstellar gas metallicity, $M_{ej}$ and $M_{ev}$ are the total ejected mass and the mass loaded by thermal evaporation. The results of the calculations are presented in Figure 1. Figure 1a displays the extreme case without any mass loading and therefore represents the upper limit for the metallicity of a superbubble. Figure 1b represents a more realistic case, with dilution caused by the low metallicity ISM. In this case the oxygen abundance reaches its maximum $Z_O \sim 2Z_{\odot}$ after 6Myr of evolution and then falls slowly to the solar value after 10Myr to finally approach $0.1Z_{\odot}$ at the end of the starburst activity.

These results are in contradiction with the previous estimates of the X-ray emitting gas metallicities based on the analysis of the ROSAT data. However, as mentioned by Strickland & Stevens (1998) the low, subsolar metallicities most probably come from the single temperature model used to fit the ROSAT spectra. Another possible solution to the low abundance problem has been indicated by Breitschwerdt (2003), who provided a detailed analysis of the non-equilibrium ionization model.

The recent estimates of the hot gas metal abundances in the starburst galaxy NGC 1569 by Martin, Kobulnicky, & Heckman (2002), are based on two temperature model and show an excellent agreement with our theoretical predictions. The $\alpha$ element metallicities for a starburst with the age between 10Myr to 20Myr have been best fitted by $Z_{\alpha} = 1.0Z_{\odot}$, and abundances higher than solar have not been excluded.

The ultimate fate of metals released within the starburst regions has been intensively debated in recent years (see Kunth; this volume and references therein).
Hydrodynamics and chemical evolution of starburst-driven outflows

Figure 1. The oxygen and iron contents of superbubbles as a function of time, in solar units. Panels a) and b) present the hot gas metallicity without and when considering the evaporation of the cold outer shell, respectively.

It is highly dependent on the kinematic properties of the host galaxy (Silich & Tenorio-Tagle 2001). Supergalactic winds rapidly develop in fast rotating systems with a disc-like ISM distribution and are less likely in slow rotating galaxies with a thick-disc or a spherical gas distribution. The metallicity-flattening relation revealed by Barazza & Binggeli (2002) that shows that rounder dwarf ellipticals tend to be more metal-rich, may support these conclusions.

3. Supergalactic wind

Energetic starbursts, evolving in a flat disc-like ISM, are able to drive their associated shock waves to the outskirts of their host galaxies, leading to the development of supergalactic winds. It is usually assumed that within the region of star formation the matter ejected by strong stellar winds and supernova explosions is fully thermalized by means of random collisions. This generates the high central temperature and large overpressure that initiates the metal-rich gas outflow. There, the mean total energy $L_{SB}$ and mass $\dot{M}_{SB}$ deposition rates control, together with the actual size of the star forming region $R_{SB}$, the properties of the resultant outflow. After crossing $r = R_{SB}$ the gas is immediately accelerated by steep pressure gradients and rapidly reaches its terminal velocity $V_t$. This is due to a fast conversion of thermal energy, into kinetic energy of the resultant wind. The free wind analytic solution of Chevalier & Clegg (1985) assumes that the thermalized gas freely expands out of the star forming region and then adiabatically cools down approaching an $r^{-4/3}$ temperature distribution.
3.1. The steady state solution

Here we study the true physical properties of such well developed free wind outflows, taking into consideration strong radiative cooling. Following Chevalier & Clegg (1985) we assume a spherically symmetric wind, unaffected by the gravitational pull caused by the central star cluster. The equations that govern the steady gas outflow away from the star forming region are:

\[
\frac{1}{r^2} \frac{d}{dr} \left( \rho ur^2 \right) = 0, \quad (3)
\]

\[
\rho \frac{du}{dr} = - \frac{dP}{dr}, \quad (4)
\]

\[
\frac{1}{r^2} \frac{d}{dr} \left[ \rho ur^2 \left( \frac{u^2}{2} + \frac{\gamma}{\gamma - 1} \frac{P}{\rho} \right) \right] = -Q, \quad (5)
\]

where \( r \) is the spherical radius, and \( u(r), \rho(r) \) and \( P(r) \) are the wind velocity, density and thermal pressure, respectively. \( Q \) is the cooling rate \((Q = n^2 \Lambda)\) where \( n \) is the wind number density and \( \Lambda \) is the cooling function.

![Figure 2. Superwinds. a) Temperature distribution for adiabatic and strongly radiative solutions. b) The two possible outcomes, hot and cold winds, as function of the parameter space.](image)

3.2. The impact of radiative cooling

A first order of magnitude estimate of whether or not radiative cooling could affect the thermodynamics of superwinds, results from a comparison of the radiative cooling time with the characteristic dynamical time scale:

\[
\tau_{\text{cool}}(r) = \frac{3kT}{n \Lambda}, \quad \tau_{\text{dyn}}(r) = \int_{R_{SB}}^{r} \frac{dr}{u(r)}, \quad (6)
\]
Our calculations show that both the velocity and the density distributions remain practically unaffected by radiative cooling. However, if radiative cooling becomes efficient, the temperature distribution strongly deviates away from the adiabatic solution forcing the gas to soon reach temperature values of the order of $10^4$ K (see Figure 2a).

Figure 2b implies that radiative cooling may become efficient for compact massive star clusters. If the initial wind parameters ($L_{SB}$ and $R_{SB}$) intersect below the corresponding terminal velocity curve, cooling will be inefficient and deviations from the adiabatic solution would be negligible. However, if the initial wind parameters intersect above the corresponding terminal velocity curve, radiative cooling is expected to become important, causing a major impact on the appearance of superwinds.

3.3. The radiative mode observational implications

Cooling provides significant modifications of a superwind internal structure (see Figure 3), bringing the outer boundary of the X-ray emitting zone and inner boundary of the cold envelope closer to the star cluster. This in turn modifies the predicted X-ray and $H_\alpha$ luminosities. The X-ray emission vanishes at large distances and arises only from zones close to the star forming region, thus leading to a drop in the total X-ray luminosity.

The trend of the $H_\alpha$ emission is different. When cooling sets in, much denser superwind layers acquire temperatures below $10^4$K. These are to be ionized by the central star cluster and by the soft X-ray photons to become visible in the optical line regime. This causes an increase in the $H_\alpha$ luminosity. For compact star clusters the difference between the adiabatic and radiative model predictions may reach almost two orders of magnitude.
4. Conclusions

The results from the calculations presented here imply that:

- The metallicity of superbubbles vary with time and can easily exceed the solar value even if the host galaxy ISM has a low metal abundance. The effects of metal contamination are most noticeable during the first 10 Myr of the bubble evolution.

- Galactic superwinds driven by compact and powerful starbursts undergo catastrophic cooling close to the star cluster surface and establish a temperature distribution radically different to that predicted by adiabatic calculations.

- The fall of the superwind temperature leads to a smaller zone radiating in X-rays and decreases the superwind X-ray luminosity.

- At the same time cooling brings the inner radius of the warm ionized gas envelope closer to the star cluster. This increases the estimated H\textalpha luminosity and predicts a low-intensity broad (~1000 km s\(^{-1}\)) line emission component.

Acknowledgments. The authors feel honoured to have attended this special meeting and acknowledge financial support from CONACYT (México) grant 36132-E.

References

Barazza, F.D. & Binggeli, B. 2002, astro-ph/0209112
Breitschwerdt, D. 2003, in RevMexAA Conf. Ser. Winds, Bubbles and Explosions, (in press)
Chevalier, R.A. & Clegg, A.W. 1985, Nature, 317, 44
Martin, C.L., Kobulnicky, H.A. & Heckman, T.M., 2002, ApJ, 574, 663
Kunth, D. 2003, This volume
Silich, S. & Tenorio-Tagle, G., 2001, ApJ, 552, 91
Silich, S.A., Tenorio-Tagle, G., Terlevich R., Terlevich E. & Netzer H., 2001, MNRAS, 324, 191
Strickland, D.K. & Stevens, I.R. 1998, MNRAS, 297, 747

Discussion

Casiana Muñoz-Tuñón: Do your results imply that cooling may affect the evolution of superbubbles?

Silich: No, we have considered the late post-blowout stage, when the reverse shock reaches the outskirts of the galaxy and the outflow approaches a free-wind steady state regime.