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FEEDBACK FROM MASSIVE STAR WINDS

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RESUMEN

En esta contribución se revisa el conocimiento teórico actual del impacto que los vientos de estrellas masivas tienen en el medio interestelar (ISM). Dichos viento son potencialmente una importante fuente de momento al medio interestelar, pero en la práctica el aporte de momento depende fuertemente del grado de mezcla entre el material del viento chocado a altas temperaturas y el gas más frío que lo rodea o está embebido en él. Este proceso de mezcla permanece aún poco entendido. Aquí se discuten las diferentes posibilidades que pudieran existir.

ABSTRACT

Our current theoretical understanding of the impact of winds from massive stars on the interstellar medium (ISM) is reviewed. Such winds have the potential to be a significant source of momentum to the ISM. In practice, the momentum boost is highly sensitive to the degree of mixing between the hot shocked stellar wind material and surrounding or embedded colder gas. This mixing remains an ill-understood process. The range of possibilities that might exist is discussed.

Key Words: galaxies: ISM — ISM: bubbles — ISM: kinematics and dynamics — stars: early-type — stars: massive — stars: winds, outflows

1. INTRODUCTION

Feedback processes, caused by massive star winds, radiation fields, and supernovae (SNe) are a key requirement of modern galaxy formation and evolution theories. They are necessary in order to obtain the observed galaxy populations, to reduce star formation to the observed rates, and to move gas and metals out of galaxies via galactic winds. Of the three processes noted, SNe are believed to be the dominant stellar input responsible for generating and maintaining the turbulent pressure that regulates the star formation rate within galaxies, and to create the hot phase of the ISM. Without SN feedback, galaxy models form stars too efficiently.

The key parameter for SN feedback is the amount of radial momentum that each supernova remnant (SNR) injects at the end of its life. This determines the amplitude of the turbulent gas motions, which limit gravitational condensation and collapse, and ultimately limits and regulates star formation. However, it has proven tricky to add SN feedback into galaxy and cosmological simulations. Only in the very latest prescriptions has SN-driven feedbak become independent of numerical resolution (e.g. the FIRE-2 algorithm implemented by Hopkins et al. 2018). However, *what* is implemented may still be inaccurate, as simulations have yet to capture the full complexity of real SNRs, including the effect of clustering and multiple SN explosions.

While SNe dominate on large scales, it appears that early (pre-SN) feedback is needed to explain the short feedback timescale required to explain the relative dearth of molecular material around young massive stars (Kruijssen et al. 2019). The relative importance of stellar wind and radiative feedback may further increase if massive stars struggle to explode at all (e.g. Smartt 2015; Sukhbold et al. 2016), or if the stellar initial mass function extends significantly past 100 $M_\odot$ (Crowther et al. 2016), is top heavy (Schneider et al. 2018), or non-universal (Yan et al. 2023).

2. WIND-BLOWN BUBBLE THEORY

Classical wind-blown bubble (WBB) theory (Pikelner 1968; Dyson & de Vries 1972; Avedisova 1972; Falle 1975) deals with the expansion of an energy-driven bubble in a low-pressure medium with no cooling of the hot interior gas and no mass-loading. In such circumstances, the winds from very massive stars have the potential to inject into the ISM via their WBBs an amount of radial momentum that is comparable to that injected by individual SNRs.

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2.1. *Mass-loaded WBBs*

Mass-loading of WBBs describes the injection of material into the hot bubble interior from either cold material in the swept-up shell or from cold clouds or clumps in the ambient medium that are over-run as the bubble expands.

The thermal evaporation of mass from the cold dense shell into the hot bubble interior was first studied by Castor, McCray & Weaver (1975) and Weaver et al. (1977). Because cooling at the interface was not considered, only the interior structure of the bubble is altered, and there is no effect on the bubble energetics, expansion rate or radial momentum. If cooling *is* considered, the evaporative mass flux into the bubble interior reduces by a factor of $3 - 30$ (El-Badry et al. 2019). However, the energy loss resulting from the cooling reduces the expansion rate and radial momentum of the bubble (the latter by a factor of 2). One caveat is that the simulations by El-Badry et al. (2019) were 1D, so it was not possible to explicitly model the instabilities at the hot-cold interface. Instead, the effects of turbulent mixing and heat diffusion were parameterized with an effective conductivity, and the true value may be greater than supposed.

The effect of mass-loading from overrun embedded clumps on WBBs was first investigated with 1D simulations by Arthur et al. (1993) and Arthur et al. (1996). The injected mass is assumed to be rapidly mixed, and radiative losses at the hot-cold interfaces around the clumps are assumed to be unimportant. This allows the mass-loaded bubbles to maintain interior gas at temperatures in excess of $10^6\,\mathrm{K}$ (unless the mass-loading is very strong). In these simulations, the global rate of mass injection increases with time, scaling roughly with the volume of the bubble. The models were applied to the Wolf-Rayet ring nebula RCW 58, and were able to reproduce the broad velocity range of the ultraviolet absorption features observed towards the central star.

More recently, Pittard (2022) investigated the behaviour of a WBB subject to mass-loading from embedded clumps where the global rate of mass injection was instead assumed to scale with the mass-loss rate of the star. The amount of mass injection could also be limited by the available reservoir of cold mass. Again, the bubbles were found to maintain hot interiors, and are still able to do significant PdV work (momentum boost) on the swept-up gas, though are smaller, have less retained energy, and have reduced radial momentum than bubbles without any mass-loading. The assumption of non-radiative mixing interfaces in all three of these works is likely to lie at the extreme end of possibilities, though remains plausible if the temperature of the interface $T \lesssim 8000\,\mathrm{K}$, and/or if the clumps are small (for more details see Pittard 2022).

2.2. *Multi-dimensional simulations of WBBs*

WBBs typically expand into a complex, inhomogeneous environment. Harper-Clark & Murray (2009) posited that in such cirumstances the swept-up shell may fracture, allowing hot interior gas to vent out, further reducing the interior pressure and the expansion rate and size of the bubble. Three-dimensional simulations reveal that the shocked wind finds paths of least resistance through the clumpy surroundings, flowing around and past dense clumps which become entrained in the flow (Rogers & Pittard 2013; Dale et al. 2014). The dense clumps are pushed away and are eventually destroyed by the action of the wind(s).

The effect of large-scale magnetic fields on the evolution of a gravitationally bound cloud, star formation, and subsequent stellar wind feedback was investigated by Wareing et al. (2017) and Wareing et al. (2018). If the cloud collapses preferentially along the field lines, the morphology of the background gas and magnetic field can efficiently direct subsequent stellar wind feedback away from denser molecular material. This offers an elegant solution to the “missing wind” problem in the Rosette Nebula (Wareing et al. 2018).

2.3. *Efficiently-cooling WBBs*

Much work in the literature finds that WBBs can efficiently cool (e.g. Geen et al. 2015; Haid et al. 2018), and thus produce little PdV work. The cooling predominantly occurs at the fractal-like interface between the cooler gas in the shell and hotter gas in the bubble interior, and its rate is dominated by turbulent mixing (Lancaster et al. 2021a,b). Star formation and stellar wind feedback were examined together by Lancaster et al. (2021c). Cooling is found to be very efficient in the denser clouds, but becomes insignificant on cluster scales at later times after most of the gas has turned into stars (cooling may remain significant on larger scales where the swept-up shell exists, but this effect was not captured by this simulation). However, in all these works the mixing rate (and thus cooling) is likely dominated by numerical diffusion, and it remains unclear if WBBs actually cool efficiently.

3. SUMMARY AND CONCLUSIONS

Stellar winds and radiation appear to be responsible for clearing molecular gas out of massive star-forming regions. However, the complexity of real environments means that it is still unclear how efficiently actual stellar wind bubbles cool, and how much PdV work they can do to boost their radial momentum. These issues are likely to be dependent on the environment, the assumed IMF (e.g. the maximum stellar mass), and the timing (cooling may become ineffective once most of the gas mass has formed stars and/or being expelled from the star forming region). It is likely that there will be significant diversity between one bubble and the next.

A final issue is that not all numerical simulations of stellar wind feedback in the literature had the necessary spatial resolution for the bubble to correctly form and inflate. These bubbles missed their highest pressure phase when young and thus did not achieve their correct radial momentum (for further details see Pittard et al. 2021).

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