Massive Stellar Clusters and Superwind Engines in the Antennae

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Abstract. The youngest super star clusters (SSCs) in the Antennae Galaxies (NGC 4038/39) drive supersonic mass-loaded outflows. High-resolution Keck/NIRSPEC spectroscopy reveals broad, spatially extended Brγ emission lines that are well-fit by simple wind models. Cluster mass-loss rates are up to 1.5 M$_\odot$ yr^{-1} and terminal velocities are up to 205 km s^{-1}. These emission-line clusters (ELCs) constitute at least 15% of the star formation rate in the Antennae, and their high star formation efficiencies imply that they will probably evolve into bound SSCs. The youngest ELC outflows are driven primarily by stellar winds, and they efficiently entrain ambient matter. They transfer or dissipate most of their energy and momentum in a hot or cool medium that does not emit Brγ. ELCs are the individual engines that power galactic-scale superwinds, viewed in their earliest evolutionary stage.

1. Mass-Loaded Outflows from Emission-Line Clusters

We discovered broad, supersonic Brγ emission in Keck/NIRSPEC echelle spectra of the youngest SSCs in the Antennae (Gilbert 2002). The Brγ profiles are well resolved (spectral resolution was 12 km s^{-1}), have widths of 60–105 km s^{-1} FWHM, and exhibit high-velocity non-Gaussian wings (Fig. 1). We dub these broad-line SSCs emission-line clusters (ELCs). Our incomplete sample of ELCs comprises 15% of the total SFR in the Antennae, and estimates of their star-formation efficiency (30–70%) suggest that they may evolve into bound SSCs, which in turn may evolve into globulars (Gilbert 2002). ELCs are typically more compact ($d \sim 40 - 80$ pc), denser, and brighter than giant extragalactic H II regions (GHIIRs), with Q $= 10^{51} - 10^{53}$ s^{-1}, and their recombination line fluxes and widths exhibit the same correlation seen for GHIIRs (Gilbert 2002).

Brγ line fluxes and K magnitudes imply ELC ages of 3–8 Myr and masses of $10^5 - 10^7$ M$_\odot$ (using Starburst99 models, Leitherer et al. 1999). Comparing the virial line widths (from ELC masses and sizes) with observed ones suggests that *much of the gas in ELC outflows is unbound.*

We determine the mass-loss rates of ELCs, by modeling their supersonic Brγ profiles with a semi-empirical β-wind law that is successful for radiation-driven wind lines of hot stars (e.g. Kudritzki & Puls 2000), and provides excellent fits to
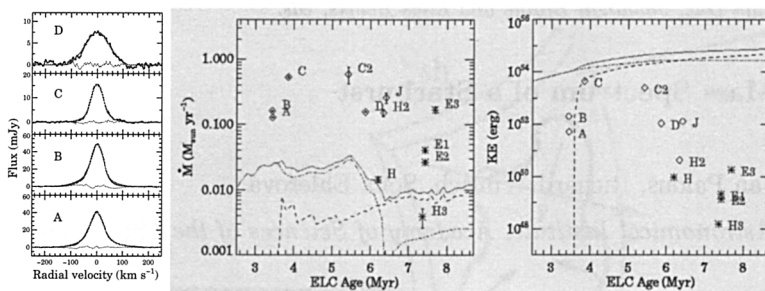
Figure 1. Supersonic Brγ profiles of four ELCs with overplotted wind models and fit residuals (left). Mass-loss rates (center) and kinetic energy (right) measured for ELC outflows (points, normalized to a 10^6 $M_\odot$ cluster). Curves are predictions from Starburst99 for a cluster's stellar winds (dotted), SNe (dashed), and their sum (solid).

our spectra (Fig. 1). ELC mass-loss rates in ionized gas ($\dot{M}_{\text{HII}}$) are $0.006 - 1.5$ $M_\odot$ yr^{-1}. Fig. 1 compares observed normalized $\dot{M}_{\text{HII}}$ with that provided by stellar ejecta (winds and supernovae) in a Starburst99 cluster of 10^6 $M_\odot$. For most ELCs we detect over an order of magnitude more outflowing photoionized gas than is ejected directly from stars; thus *ELC outflows efficiently entrain matter*. Either older ELCs entrain matter less efficiently, or they have swept away most of their reservoir of neutral gas. Another indication that we are not observing mass lost directly from hot stars comes from the low (≤ 205 km s^{-1}) terminal velocities of ELC outflows. They are about ten times less than the terminal velocity of a single O star wind, and is probably due to the interaction of many individual winds, photoevaporative flows, (in older clusters) supernova explosions, and ultimately the collision with ambient neutral gas.

Fig. 1 also displays the measured and predicted kinetic energies (KEs) of the outflows. In Brγ we detect only a small fraction of the KE available from winds and SNe: *ELC outflows have a high thermalization efficiency*. The rest of the KE must reside in a hotter and/or cooler medium. Stellar wind shocks generate X-rays, and Chandra observations reveal possible counterparts for some ELCs (e.g. Zezas et al. 2002). Efficient thermalization of mechanical energy in mass-loaded winds is common in large-scale superwinds (e.g. M82, Suchkov et al. 1996), the earliest phase of which may be taking place in the Antennæ.

References

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