

The importance of Wolf-Rayet ionization and feedback on super star cluster evolution

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The feedback from massive stars is important to super star cluster (SSC) evolution and the timescales on which it occurs. SSCs form embedded in thick material, and eventually, the cluster is cleared out and revealed at optical wavelengths – however, this transition is not well understood. We are investigating this critical SSC evolutionary transition with a multi-wavelength observational campaign. Although previously thought to appear after the cluster has fully removed embedding natal material, we have found that SSCs may host large populations of Wolf-Rayet stars. These evolved stars provide ionization and mechanical feedback that we hypothesize is the tipping point in the combined feedback processes that drive a SSC to emerge. Utilizing optical spectra obtained with the 4m Mayall Telescope at Kitt Peak National Observatory and the 6.5m MMT, we have compiled a sample of embedded SSCs that are likely undergoing this short-lived evolutionary phase and in which we confirm the presence of Wolf-Rayet stars. Early results suggest that WRs may accelerate the cluster emergence.

1 Introduction

The highest concentrations of Wolf-Rayet stars (WRs) are found extragalactically in massive and super star clusters (SSCs). These bright, blue star clusters have masses as high as $10^6 M_{\odot}$ and host hundreds to thousands of massive stars, which interact with each other, in a single dense cluster. These regions are thus equivalent to, or more massive than, the closest well-known example R136 in the Large Magellanic Cloud. As SSCs are so rich, these are some of the most extreme regions of star formation.

A cartoon picture of SSC evolution has developed in which SSCs form as scaled-up versions of single massive stars in the Milky Way (Johnson 2002), during which we expect different observable signatures at each stage. A SSC forms from a thick, dense molecular cloud; the proto-SSC is thus embedded in and obscured by an envelope of natal material. Soon, massive stars forming within the cluster ionize this surrounding material. A SSC at this evolutionary stage is detectable as a radio continuum source with thermal emission, which is indicative of this dense young H II region (e.g. Kobulnicky & Johnson 1999). As the stars continue to evolve and more form, feedback will clear out the surrounding material and will ultimately produce an optically visible cluster.

Yet, how these SSCs emerge from the natal envelope is not yet well understood despite implications for the fate of the cluster itself as well as for the nearby environment and host galaxy. For instance, a lack of understanding how the ionizing radiation escapes from individual H II regions may be hindering current cosmic simulations (Paardekooper et al. 2011). The future of a cluster is impacted by the removal of natal gas, as this can effect further star formation efficiencies (even halting further star formation, Baumgardt & Kroupa 2007) and the cluster's ability to stay bound and thus survive (Pfalzner & Kaczmarek 2013). Understanding cluster emer-

gence has been extremely difficult, largely because these are messy environments with many physical mechanisms at play. Feedback processes include: direct stellar radiation; photoionization; pressure from cold, warm (ionized), and hot gas; dust-processed IR radiation; protostellar wind and jets; and later, winds and supernova from massive stars (e.g. Lopez et al. 2011).

Simulations and observations have recently concentrated on identifying the dominant feedback mechanism. However, simulations often are limited in some capacity. Modeled star clusters are typically less massive than SSCs, and the input coupling of the feedback to the cloud material is not yet well founded (Rogers & Pittard 2013). Fortunately, as simulations are becoming more powerful, they are able pull out more details about how clusters emerge: for instance, in comparing the effects of stellar winds versus photoionization. Dale et al. (2014) find that photoionization dominates the energetics during star cluster evolution, yet the additional inclusion of winds is necessary to get observed morphologies of the produced H II region.

Observationally, a consensus on the dominate feedback mechanism has not been reached. Lopez et al. (2011) compares the pressures due to various feedback mechanisms (stellar radiation, dust-processed IR radiation, and the different temperature gas components) and finds that radiation pressure dominates in 30 Dor. Alternatively, an independent study by Pellegrini et al. (2011) concludes that hot gas dominates instead. Moreover, a larger expanded sample of H II regions in the Magellanic Clouds finds that the warm ionized gas pressure dominates (Lopez et al. 2014).

By highlighting an overlooked yet potential source of feedback instead, we provide a fresh look into this important evolutionary transition through the identification of an emerging massive star cluster. This

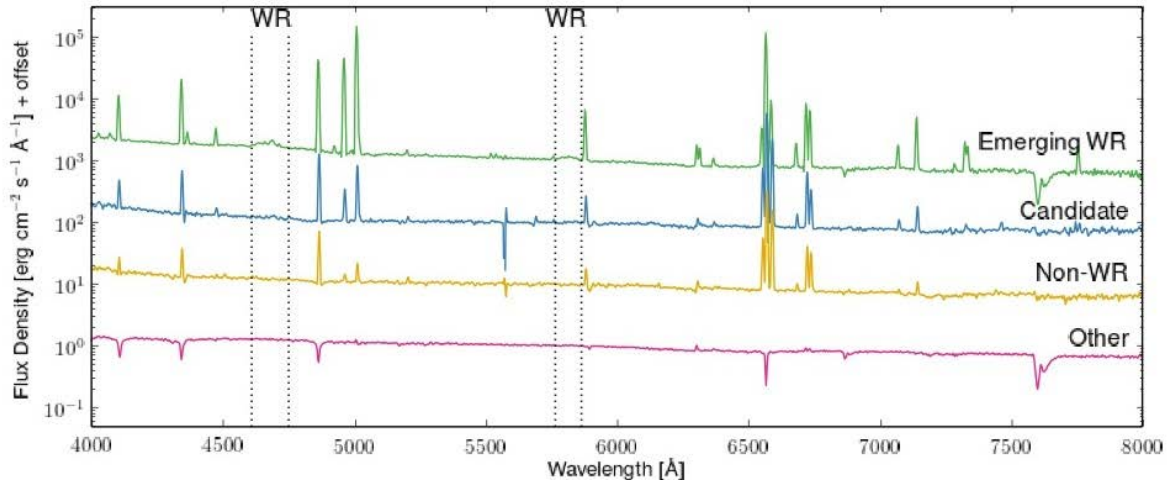


Fig. 1: An example optical spectrum observed with the 4m Mayall Telescope at KPNO and the 6.5m MMT of each type of class within our sample. Dashed lines show where the broad WR features (‘bump’) lie.

star cluster is a prime example of this phase as enshrouding natal material is being drastically altered and evacuated by a massive star population containing WRs.

2 S26 - discovery of emerging WR clusters

S26 in NGC 4449 was identified as a partially-embedded radio continuum source (Reines et al. 2008) with a thermal emission component. An extragalactic thermal radio detection of an H II region, which is rather rare (Aversa et al. 2011), indicates youth and either vast size or high density. Archival *Hubble Space Telescope* images show that S26 also quite bright optically and currently emerging. When we obtained optical spectra of S26, we discovered a surprising feature known as the WR bump (Reines et al. 2010; Sokal et al. 2015) due to integrated stellar emission from WRs.

Given our previous understanding of timescales, one would not expect for WRs to appear until after a star cluster has emerged. Thus their simultaneous presence with thermal radio emission may suggest that S26 remained embedded until the WRs help it emerge (Sokal et al. 2015). Additional evidence for ongoing feedback is also seen in the infrared SED from archival Spitzer and Herschel Space Telescope images and a possible nebular bipolar outflow in the cluster center (Sokal et al. 2015). Because of S26, we hypothesize that WRs may provide the tipping point in the combined feedback processes that drive a SSC to emerge (Sokal et al. 2015).

3 Finding more emerging WR clusters

3.1 Observational survey

We have carried out an observational survey to identify more clusters like S26. Targeting radio continuum sources with thermal emission similar to S26 in star-forming galaxies, we obtained optical spectra with the 6.5m MMT at the Fred Lawrence Whipple Observatory and the 4m Mayall Telescope at Kitt Peak National Observatory to search for the WR bump. In line with a classification scheme from Whitmore et al. (2014), we find clusters undergoing the emerging phase via detected radio emission, optical continuum, and optical lines. By searching for emerging clusters with WR features, we are looking specifically for ‘emerging WR clusters.’

3.2 Success! and classifications

Clear detections of the WR bump are found in many targets – vastly expanding our sample of emerging WR clusters. However, there are many sources in which we do not see a clear WR bump, these range from very different objects, to H II regions without any bump whatsoever, and to sources with possible or only nebular WR features. As such, we have classified our sample of radio-selected sources as ‘emerging WR’ if the WR bump is detected, ‘candidate’ if there is a non-significant detection of the WR bump, ‘non-WR’ if the WR bump is not detected, and ‘other’ if the spectra do not resemble emission line spectra expected of H II regions (Sokal et al. 2015b, in prep). Example spectra and the distribution of the classes are shown in Fig. 1 and 2.

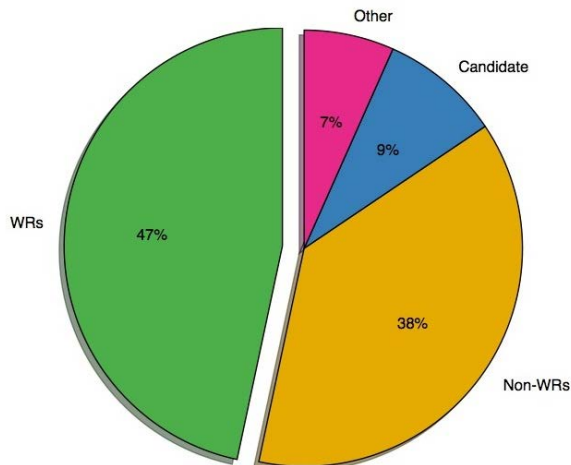


Fig. 2: The distribution of the classes observed in our sample. Emerging WR clusters are the most common amongst the classes, and if the Other class is omitted, these clusters makes up more that 50% of the sample.

3.3 WRs and cluster evolution

With this survey, we have identified 21 emerging WR clusters by searching for the WR bump in a sample of 45 radio-selected sources. We find we do not preferentially detect or observe either the emerging WR cluster class nor the non-WR cluster class. Classes with and without WR features show similar observed luminosity distributions and span the same parameter space in radio properties.

Thus, the observed commonality of the WRs is an important result: a clear detection of the WR bump is observed in $\sim 50\%$ of our radio-selected sample (see Fig. 2). We note that just like proving single stars are single, it is difficult to prove that WRs are not present in a given integrated spectrum – rather, one can only show that they are. Still, a compelling percentage of the sample hosts WRs.

Moreover, we have found there may be large differences between these two classes. The distribution of cluster ages shows that the emerging WR clusters tend to be younger than sources without WR features. Similarly, the emerging WR clusters in general are found to have lower extinctions, as shown in Figure 3. Our preliminary results suggest the sources with the highest extinctions do not have WRs (are non-WR clusters) and are also older (Sokal et al. 2015b, in prep). This may suggest that clusters without significant populations of WRs remain embedded for longer periods of time than clusters which host WR stars. This scenario is in agreement with the hypothesis derived from S26 by Sokal et al. (2015) that WRs are evolutionally important for a cluster to emerge.

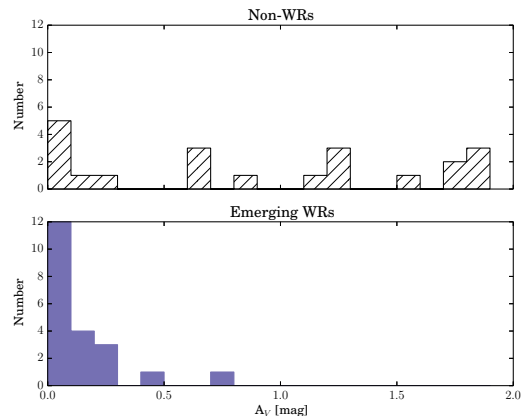


Fig. 3: The measured extinctions of the emerging WR cluster and non-WR cluster classes. We see that sources with WR features are less extinguished on average.

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Shweta Srivastava: You mentioned some of the clusters are obscured in radio. At which wavelength and angular resolutions were these clusters observed in radio?

Kimberly Sokal: They are selected from the literature with a variety of observations at different wavelengths. They all included 6 cm observations but then to get the radio spectral index α , some had 20 cm, others 3.4 cm. It is unfortunate, but there are only a handful of galaxies with actually detected, multiple sources.

Joanne Bibby: How do you know that when you see no WR-bump it's just not due to line dilution where the WR emission is hidden by a large continuum?

Kimberly Sokal: Yes, I can't know. Which is why I leave it at "at least 50%" because it really is a lower

limit, also can be affected by weak-lined WRs and aperture effects (we heard about this week).

John Eldridge: If you look at your BPT diagram you'll see that it goes right into the area predicted by binary models which and all relevant data is on the website.

Paul Crowther: In view of the spatial resolution achieved at > 2 Mpc distances, the central cluster of 30 Dor (R136) has an age below 2 Myr, yet shows a WR bump from very massive stars whereas a nearby older modest cluster R140 dominates the WR bumps on a scale of 30×30 pc.

Kimberly Sokal: Yes, yes. We hope that with the largest sampling some of that averages out. Apertures and line of side effects are both unavoidable.

