The Most Massive Extragalactic Evolved Stars

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The recent identification of an emerging class of evolved self-obscured 25–60 $M_{\odot}$ stars in galaxies at ~1–4 Mpc has for the first time created the opportunity to observationally investigate a statistically significant number of stars undergoing episodic mass loss. While our current efforts to identify these rare objects in a short-lived yet consequential evolutionary phase primarily rely on archival *Spitzer* IRAC (3.6–8 μm) and MIPS (24 μm) images, they can be studied far more optimally at 10 ~ 28 μm with the *Webb* taking advantage of MIRI's order-of-magnitude-higher resolution.

Episodic mass loss from evolved stars

Stellar mass loss determines the structure and terminal mass of evolved massive stars and the presence of circumstellar material. This in turn calibrates the energetics and observed properties of some of the highest energy phenomena in the universe such as core-collapse supernovae, gamma-ray bursts, neutrino bursts, and gravitational wave bursts. However, there are no good prescriptions on how to include large, episodic, mass-loss events into theoretical models. Such complicated objects are difficult to comprehend in a theoretical framework due to the computational complexities involved in modeling a dynamically unstable, short (decades to centuries) evolutionary phase in the ~10 million-year lifetimes of the most massive ($\gtrsim$25 $M_{\odot}$) stars. Observationally, the overall small number of stars detected in this ultra-short, yet eventful, evolutionary phase limits us. Searching for these stars in the Galaxy is hard because of distance uncertainties, as well as having to look through the crowded galactic disk.

A full understanding of the evolution of these stars therefore requires exploring galaxies beyond the Milky Way. Surveys of nearby galaxies are better defined and when used to build larger samples of younger systems (having a shorter time since mass ejection), can be studied to better understand their evolution. At extragalactic distances, a self-obscured massive star would appear as a bright, red point source in IRAC images, with a relatively fainter optical counterpart due to self-obscuration. Its spectral energy distribution (SED) would generally have two peaks—an obscured optical peak, which could be absent altogether given enough absorption, and a mid-IR peak. In the *Spitzer* bands, the SED would be either flat or rising towards longer wavelengths, before turning over between 8 and 24 μm due to the presence of warm circumstellar dust. Our team concentrated on these properties to identify the extragalactic obscured massive stars.

An emerging class of self-obscured stars

In our pilot study of seven galaxies at <4 Mpc (NGC 6822, M33, NGC 300, M81, NGC 2403, NGC 247, NGC 7793), first we identified the candidate sources that are most likely to be evolved self-obscured stars. We selected sources that have a mid-IR luminosity of $>10^5$ $L_{\odot}$ in the IRAC (3.6–8.0 μm) bands, as well as a flat or rising SED in this wavelength range. Next we verified the stellar nature of the candidates utilizing ancillary multi-wavelength archival data from the *Spitzer* MIPS (24 μm), WISE, 2MASS, *Hubble* and other space- and ground-based observatories. We focused on identifying two telltale signatures of the SED of a luminous star obscured by warm circumstellar ejecta: signs of the SEDs turning over between 8 μm and 24 μm, and low optical fluxes or flux limits compared to the mid-IR peak. Finally, we determined the best fit to the verified obscured stars' SEDs by modeling radiation transfer (see Figure 1) through a spherical medium surrounding the star, which is also a good approximation for *unresolved* objects with a combination of non-spherical, patchy, and multiple shells.

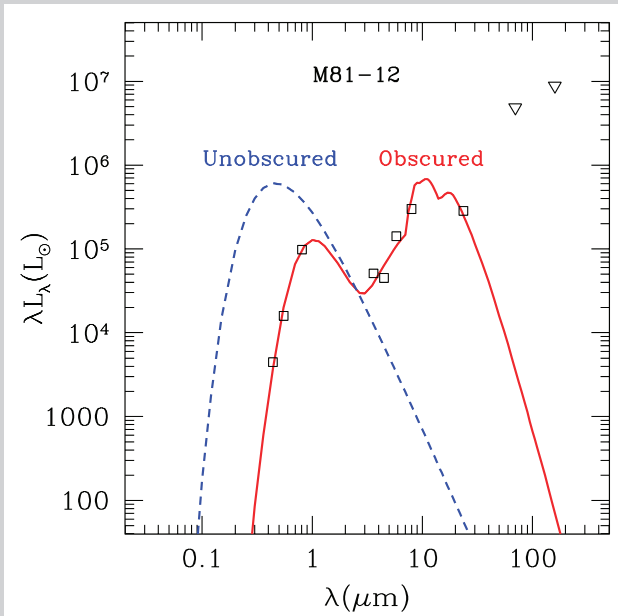

Figure 1: We determined the best fit to an obscured star's SED through radiative transfer modeling to estimate the bolometric luminosity and temperature of the underlying star as well as the mass, temperature and optical depth for the obscuring material. The solid red line shows the best-fit model of the obscured stellar SED of one of the newly identified stars in M81, while the dashed blue line shows the blackbody SED of the underlying, unobscured star.

This allowed us to estimate their bolometric luminosities and circumstellar ejecta mass. Surprisingly, we found that all the newly identified stars have bolometric luminosities within a narrow range of log $L/L_{\odot} \simeq 5.5$–6.0, which roughly corresponds to initial stellar masses of ~25–60 $M_{\odot}$. Stars enter this high optical depth phase at a rate that is consistent with all obscured stars at this mass for a negligible fraction of their ~3–10 million years' post-main-sequence lifetimes, that is, at most a few thousand

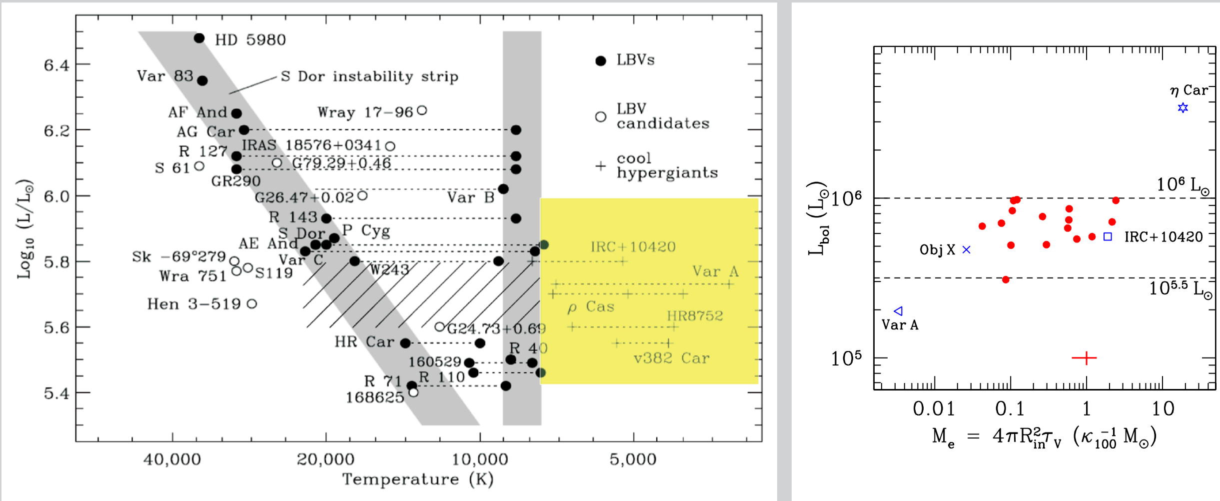

Figure 2: The evolved massive stars we found may be the "missing LBVs" (Smith et al. 2004) traversing the "Yellow Void" (Nieuwenhuijzen & de Jager 2000) like the Galactic star IRC+10420 (e.g., Tiffany et al. 2010). Smith et al. (2004) proposed that LBVs missing from the striped region on the upper H-R Diagram (*left* panel, adopted from their paper) reappear as cooler obscured giants in the yellow box. The *right* panel shows the luminosities of the sources that Khan et al. (2015) found, as a function of their estimated ejecta masses. The luminosity range enclosed by the dashed lines here is same as the yellow box on the *left* panel.

years. The number of such events a star experiences is also small: one or two, not ten or twenty. This implies that these events have to be associated with special periods in the evolution of the stars.

Extragalactic stellar astrophysics with the *Webb*

The primary limitation of the present search is *Spitzer*'s angular resolution. The *Webb*'s order-of-magnitude-higher spatial resolution will enable us to greatly reduce the problem of confusion and to expand the survey volume. Far more important will be the ability to carry out the search at 10 ~ 28 μm, which will increase the post-eruption time over which we can identify expanding circumstellar dusty ejecta, significantly improving the statistics and our ability to study the long-term evolution of these systems.

When we expand the search with the *Webb* to include more distant star-forming galaxies, we will put to test the general post-main-sequence stellar evolution scenario described by Nieuwenhuijzen & de Jager (2000) and Smith et al. (2004). They proposed that the photospheres of blueward evolving red supergiants with $\log(L/L_\odot) = 5.6 \sim 6.0$ and $T_{\rm eff} \simeq 7000$–12500 K become moderately unstable. This leads to periods of lower effective temperature and enhanced mass loss as the stars try to evolve into a "prohibited" region of the H-R diagram. With the *Webb*, we will verify if the obscured massive stars identified in a much larger number of galaxies reside in the same narrow luminosity range as the ones we identified in the pilot study of seven galaxies. This is the anticipated luminosity regime of the "bistability jump" (Vink et al. 1999) in wind speeds driven by opacity changes, which can explain the "missing LBVs" and the existence of Yellow Hypergiants with high mass-loss rates (see Figure 2).

These extremely rare stars are by definition luminous in the 3.6–24 μm wavelength range, where the *Webb* will be most sensitive. They are rare laboratories of stellar astrophysics and will be very interesting extragalactic stellar targets for mid-IR spectroscopy with the MIRI. This will give us an unprecedented view of these most massive self-obscured stars, letting us to determine their evolutionary state and the chemical composition of their circumstellar ejecta.

References

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