

Stellar Evolution, Mass Loss, and Galactic Chemical Enrichment

(Broad Scientific Goals)

During the late stages of stellar evolution, nuclear processing, internal mixing, mass loss, and circumstellar chemistry depend sensitively on initial mass, age, and perhaps other factors.

Nuclear processing creates distinctive elemental and isotopic abundance patterns in stellar cores. Mixing reaching various depths over the lifetime of a star enriches elemental abundances at the stellar surface. Mass loss recycles processed material back into the galactic chemical reservoir out of which future generations of stars will form. Complex chemistry in outflows creates a rich temporal and spatial sequence of molecules and dust that strongly constrain the physics of mass loss from evolved stars.

(Key Objectives)

Mass loss has a profound influence on the evolution and ultimate fate of massive stars. Despite research dating back to Adams & MacCormack (1935) and Spitzer's thesis (1938), the mechanisms responsible for outflows in evolved stars remains uncertain. Determining the wind acceleration mechanism is a key scientific objective for the next generation of astronomical facilities.

Observations with new facilities will be used to test and then apply new mass loss models, ultimately obtaining mass loss rates as a function of age and initial stellar mass. A second key scientific objective is the incorporation of realistic mass loss rates into existing stellar structure codes, overcoming the main uncertainty in current models of evolved stars.

Once mass loss can be predicted as a function of age, measurements of elemental and isotopic abundance will test nuclear reaction rates and models of internal mixing. Obtaining a thorough understanding of the internal structure of evolved stars is a third key objective. Knowledge of the final state of evolved stars is a necessary initial condition for models of supernovae, which serve as important cosmological distance indicators.

A final key objective is to understand the impact of mass loss on the chemistry and energy balance of the ISM. Interstellar dust is believed to form in outflows from evolved stars. Observations of circumstellar molecules and dust will determine the yield of various interstellar species as a function of progenitor mass.

(Key Measurements)

Infrared and millimeter wavelengths contain a rich sequence of molecular gas, ice, and dust features that strongly constrain temperature, density, dynamics, and composition of outflows from evolved stars. Over 50 molecular species have been measured in the nearby outflow source IRC+10216. Approximately a dozen broad dust features have been distinguished in infrared spectra of evolved stars.

Molecular line fluxes at infrared and millimeter wavelengths will constrain temperature, density, and abundances. Molecular line shifts and widths will constrain velocity fields and wind acceleration mechanisms. Isotopic abundance ratios from molecular lines will constrain nuclear reactions and mixing in evolved stars. Strengths of infrared dust features will constrain dust formation processes. Spectral energy distributions will constrain radial temperature distributions, even for unresolved sources.

For spatially resolved outflows (stellar angular diameter greater than 5 mas), molecular and dust diagnostics will be mapped as a function of position in the outflow, strongly constraining outflow models. Deviations from spherical symmetry and clumping will be directly imaged. Proper motion of clumps in the nearest sources (19 mas/yr in IRC+10216) will be measured, providing three dimensional velocity maps. Thermal and chemical evolution of individual clumps will be monitored. Linear polarization will constrain dust geometry and alignment.

Samples for studying outflows from evolved stars will consist mainly of supergiants, Miras, and proto-planetary nebulae. There is no complete catalog of stellar angular diameters, but a quick literature survey yielded 8 relevant sources larger than 20 mas, 31 sources larger than 10 mas, and 80 sources larger than 5 mas. This list is certainly incomplete and does not yet include proto-planetary nebulae.

GSMT, NGST, and ALMA will have the sensitivity to detect unresolved outflow sources throughout the Galaxy, barring extreme extinction or crowding. More detailed studies of resolved sources will be used to interpret distant sources. Evolved stars in clusters will be key targets, as progenitor mass can be inferred from the main-sequence turnoff mass.

(Synergy between GSMT and ALMA)

Complete spectral coverage is needed to constrain outflow models from the stellar surface out to large radii. Infrared diagnostics preferentially probe warmer, denser regions close to the star, whereas the millimeter lines typically form in cooler, widely distributed ejecta. Millimeter measurements constrain molecular gas chemistry and dynamics, whereas near infrared measurements probe photospheric processes, initial wind acceleration, and dust formation.

GSMT and ALMA will have comparable angular resolution (10 mas), making it possible to obtain broad spectral coverage in maps of spatially resolved outflows. For the closest

outflow sources, the motion and evolution of individual knots can be monitored. GSMT and ALMA also have roughly similar sensitivity to thermal emission from outflow sources at temperatures of 100-1000 K.

Because of the wide variety of outflow characteristics, models will be better constrained by complete wavelength coverage of individual sources, rather than disjoint measurements of two independent samples.

(Synergy with NASA Missions)

Spectral energy distributions for evolved stars typically peak at near- or mid-infrared wavelengths, so GSMT, NGST, and ALMA can study the same set of sources, despite the smaller aperture of NGST. For brighter sources, SIRTf can provide mid-infrared coverage between GSMT and ALMA.

Mid-infrared spectra contain a majority of the dust emission features used to study dust chemistry. Also, most of the flux from evolved stars is emitted at mid-infrared wavelengths, making NGST or SIRTf measurements an important constraint on stellar luminosity.

(Issues for Discussion)

- 1) Are combined measurements by GSMT, NGST, and ALMA adequate to achieve science goals?
- 2) What size sample is required to achieve science goals, especially given the diversity of outflow sources?
- 3) Could science goals be achieved without GSMT or ALMA?
- 4) What additional information is needed to demonstrate feasibility?
 - a) List of resolved targets sorted by type and angular diameter.
 - b) List of spectral features sorted by species and wavelength.
 - c) S/N calculations for various sources and spectral features.
 - d) Description of best models currently available.
 - e) ...?