# Early Stages of High-Mass Star Formation: A Multiwavelength Investigation

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by

**NAMITHA ISSAC**

**Department of Earth and Space Sciences**
**Indian Institute of Space Science and Technology**
**Thiruvananthapuram, India**

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# Abstract

Massive stars ($M \gtrsim 8\,M_\odot$), through their radiative, mechanical and chemical feedback, play a vital role in the evolution of the galaxies and hence the Universe. Given their enormous luminosity of the order of $\sim 10^5\,L_\odot$, they dictate the energy budget of galaxies through powerful winds, strong radiations and supernova events. Despite being a key player, most aspects of the processes involved in the formation of massive stars remain unclear in both the observational as well as the theoretical front. Being deeply embedded, short-lived, and rare, poses observational challenges in studying this mass regime. Though several statistical studies have been conducted to explore the generic properties of high-mass star-forming regions, observational studies focussing on individual star-forming regions are few, especially towards the the initial stages of formation.

This motivates the investigation on the early phases of high-mass star formation presented in this thesis. Towards achieving this goal, we probe two extended green objects, EGOs G12.42+0.50 and G19.88-0.53, using the data obtained from different telescopes covering a wide wavelength range. These include dedicated observations as well as archival datasets. These sources are selected based on their large angular extent and flux densities at 4.5 $\mu$m and also being embedded within infrared dark clouds. The nature of the associated ionized gas emission is examined using low-frequency radio continuum observations carried out using the Giant Meterwave Radio Telescope, India. The ionized component of both EGOs display elongated morphology, with distinct radio components. The spectral index values, lying in the range $0.3 - 0.7$, derived from the radio flux densities, indicate that both the regions are dominated by thermal bremsstrahlung emission. These values of spectral index are consistent with the radio emission arising from an ionized thermal jet. Further, several observational manifestations, like weak radio emission, linear morphology, and association with large-scale molecular outflows with the jet candidate at its centroid, are consistent with the thermal radio jet scenario interpretation from radio observations. Shock-excited lines of $H_2$ and [FeII], as seen in the near-infrared spectra towards these sources, obtained using the United Kingdom Infrared Telescope, lend further support to the ionized jet scenario. However, given the compact and almost spherical morphology of one of the radio components associated with G12.42+0.50, we investigate the nature of the radio emission under the UC H II region framework under the assumption that the emission at 1390 MHz is optically thin and arises from a spherical, homogeneous and isothermal medium. The Lyman continuum flux hence derived, translates to an ionizing star of spectral type of B1-B0.5. Given compelling evidence supporting, both, the UC H II region and ionized jet scenarios,

we are prompted to consider the coexistence of the UC H II region with the ionized jet, both powered by the same massive young stellar object.

Cold dust emission mapped at far-infrared wavelengths, reveals massive dust clumps of masses $> 1000\,M_\odot$ enveloping the EGOs. Zooming-in on the inner regions of these clumps at millimeter wavelengths with high-resolution continuum data from SMA and ALMA unravel the presence of dense and compact dust cores deeply embedded within the cold dust clumps. Based on the mass and size estimates, all the dense cores detected towards G12.42+0.50 and G19.88-0.53 have the potential to form high-mass stars. Signature of a hub-filament system is seen in the *Spitzer*-IRAC 8.0 $\mu$m and far-infrared images of G12.42+0.50 and is supported by the constructed $H_2$ column density and dust temperature maps. Detailed investigation of the molecular gas kinematics using the archival dataset from JCMT agrees with bulk motion in the filaments and suggests a likely picture of gas inflow along the filaments to the massive dust clump enveloping G12.42+0.50. The gas kinematics study using the archival datasets from the MALT90 survey and JCMT also unveils the presence of both infall activity and large-scale outflow, suggesting an early stage of massive star formation in G12.42+0.50. Probing the gas kinematics using the archival ALMA data reveals G19.88-0.53 as an active protocluster with high-mass star-forming components spanning a wide evolutionary spectrum from hot cores in accretion phase to cores driving multiple outflows to possible UC H II regions.

Investigating the star-forming Planck Galactic Cold Clump, G133.50+9.01 using the molecular line observations from the Purple Mountain Observatory reveals a picture of two colliding clouds, G133a and G133b, triggering the formation of a complex network of filaments, dense cores and YSOs. Observational evidence suggests the likelihood of the collision of the two clouds, forming a shock-compressed layer in the intersection region, characterised by broad bridging features, a characteristic signature of cloud-cloud collision. The shocked layer exhibits an arc like morphology with enhanced excitation temperature and $H_2$ column density. Conforming with magneto-hydrodynamic simulations, the formation of a complex network of filaments with 14 embedded dense cores is deduced from the SCUBA-2 850 $\mu$m map, lying along the shocked layer, where the background magnetic field is amplified in the direction perpendicular to the filaments. An over-density of Class I and II YSOs along the intersection arc advocates for collision induced cluster formation in G133.50+9.01.

The in-depth, multiwavelength studies carried out as a part of this thesis work elaborates the potential of such studies to decipher various components and processes involved during the early phases of high-mass stars. Such detailed observational studies are key to establishing the much needed database required to validate the proposed theories.