Abstract

Massive stars, despite being relatively rare, play a crucial role in shaping the dynamics and evolution of galaxies, influencing their environments through intense radiation, stellar winds, and supernova explosions. The formation of massive stars remains one of the most intriguing and challenging problems in astrophysics, requiring a comprehensive understanding of the interplay between gravity, turbulence, magnetic field, and feedback processes. Additionally, in their evolved stages, energetic feedback from massive stars accelerates particles to relativistic speeds through shocks produced by their stellar winds and explosive supernova events. These high-energy particles, or cosmic rays, play a vital role in regulating star formation, driving chemical enrichment, and influencing the interstellar medium.

To understand the intricacies of their formation mechanisms, we investigated two protoclusters, G12.42+0.50 and G19.88-0.53, using data from the ALMA Three-millimeter Observations of Massive Star-forming Regions (ATOMS) survey, along with multiwavelength archival datasets. Our analysis revealed seven cores in each of the two globally contracting protoclusters. The observed fragmentation in both protoclusters suggests thermal Jeans instability as the driving mechanism. The cores and their parent clumps, satisfying the mass-radius and surface mass density criteria for high-mass star formation, are observed to be supercritical and in gravitational collapse. Additionally, we identified several filamentary structures that intertwine and converge at the locations of the protoclusters. To explore how mass is assembled, we studied the gas kinematics at different spatial scales. On large scales, we observed gas inflow along converging filaments, likely driven by supersonic turbulence. On smaller scales, we identified intermediate-scale and small-scale sub-structures, branches and leaves, respectively. Our study of gas kinematics in these structures shows that supersonic gas motion dominates in the branches, consistent with Larson's law, while gravity-dominated motion is observed in the leaves. The transition from supersonic to subsonic/transonic motion occurs at ~0.1 pc scales, where turbulence dissipates and gravity takes over. A picture of a scale-dependent combined effect of turbulence and gravity emerges from our investigation, driving massive star formation in these protoclusters.

Using sub-millimeter data and archival radio data from the Very Large Array, we studied the ring-like H II region G24.47+0.49 and found evidence of hierarchical triggering relating three epochs of high-mass star formation in concentric rings of the H II region. The first

epoch consists of massive stars responsible for creating the H II region. Based on 4.86 GHz data, we propose that the spectral type of this star is O8.5V–O8V. The second epoch is characterized by ultra-compact H II regions and massive star-forming cores located within the swept-up inner ionized ring. These formed from the secondary collapse of swept-up material and show signatures of various evolutionary phases. Our study of molecular gas kinematics provides the first direct and unambiguous detection of an expanding molecular ring (expansion velocity of $9\,\mathrm{km\,s^{-1}}$) driven by radiation pressure and wind kinetic energy. This outer molecular ring comprises the third epoch of potential massive star-forming regions, triggered by pressure from expansion and feedback from the newly formed stars. The detected cores in this molecular ring meet the surface mass density thresholds for massive star formation, and half of them are supercritical and collapsing under gravity.

To understand the feedback in later evolutionary phases, we searched for signatures of particle acceleration in Wolf-Rayet (WR) systems under different scenarios: wind-wind and wind-interstellar medium interactions. This study was carried out using low-frequency radio data obtained with the upgraded Giant Metrewave Radio Telescope. In the wind-wind interaction scenario, we studied WR 114 and WR 142 in Band 4 (550–950 MHz) and Band 5 (1050–1450 MHz). No radio emission was detected from either star, nor was any extended emission observed. Based on these non-detections, we report upper limits for the radio flux densities and explore plausible explanations for the absence of radio emission under two frameworks: (i) stellar wind from a single star and (ii) colliding-wind binary systems. In the single-star scenario, we constrain the mass-loss rate of WR 114 to be less than $10^{-5}\,M_{\odot}\,\mathrm{yr}^{-1}$. In the colliding-wind binary scenario, based on the non-detection of synchrotron emission, we suggest that the stars are either in very wide binary systems, far from periastron or in close binary systems with an orbital separation less than 70 AU (WR 114) and 20 AU (WR 142). To probe the wind-interstellar medium interaction, we studied the WR bubble, NGC 2359, around WR 7 using Band 3 (250–500 MHz) and Band 4 (550–950 MHz) data and archival radio datasets. NGC 2359 shows a complex filamentary bubble morphology in radio, optical, and infrared maps, indicating the presence of interaction regions. The spectral energy distribution between 150 MHz – 8.7 GHz reveals a slope of ≈ -0.5 above 1.4 GHz, consistent with optically thin synchrotron emission, which is observational evidence for particle acceleration. A turnover is seen below 1.4 GHz, likely caused by internal free-free absorption suppressing synchrotron radiation. This is only the second detection of non-thermal radiation from a stellar bubble around a single massive star. Our findings show that wind-interstellar interactions for isolated WR stars can accelerate particles to relativistic speeds and support the idea that they are key sources of Galactic cosmic rays.