Do protostellar fountains shape the regional core mass function? *

Jin-Zeng Li¹, Claudio Carlos Mallamaci², Ricardo César Podestá², Eloy Actis Vicente², Ya-Fang Huang¹ and Ana Maria Pacheco²

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; ljz@nao.cas.cn
² Observatorio Astronómico Félix Aguilar Universidad Nacional de San Juan Argentina, Av. Benavidez Oeste 8175 - J5413FHL Chimbás - San Juan, Argentina

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Abstract The emerging massive binary system associated with AFGL 961 signifies the latest generation of massive star and cluster formation in the Rosette Molecular Complex. We present the detection of a compact cluster of dusty cores toward the AFGL 961 region based on continuum imaging at 1.3 mm by the Submillimeter Array. The binary components of AFGL 961 are associated with the most intensive millimeter emission cores or envelopes, confirming that they are indeed in an early stage of evolution. The other massive cores, however, are found to congregate in the close vicinity of the central high-mass protostellar binary. They have no apparent infrared counterparts and are, in particular, well aligned transverse to the bipolar molecular outflows originating from AFGL 961. This provides evidence for a likely triggered origin of the massive cores. All 40 individual cores with masses ranging between 0.6 and 15 $M_\odot$ were detected above a $3\sigma$ level of 3.6 mJy beam$^{-1}$ or $0.4 M_\odot$, based on which we derive a total core mass of 107 $M_\odot$ in the AFGL 961 region. As compared to the stellar initial mass function, a shallow slope of 1.8 is, however, derived from the best fit to the mass spectrum of the millimeter cores with a prestellar and/or protostellar origin. The flatter core mass distribution in the AFGL 961 region is attributed here to dynamic perturbations from the massive molecular outflows that originated from the massive protostellar binary, which may have altered the otherwise more quiescent conditions of core or star formation, enhanced the formation of more massive cores and, as a result, influenced the core mass distribution in its close vicinity.

Key words: stars: formation — stars: individual (AFGL 961) — stars: circumstellar matter — stars: mass function

1 INTRODUCTION

The stellar initial mass function (IMF), which appears to be largely universal (Bonnell et al. 2007), is a key issue in the fields of star formation and galaxy evolution. Strenuous theoretical efforts have been made to explore the physical processes which may be involved in its origin (Elmegreen 2001; * Supported by the National Natural Science Foundation of China.
Bonnell et al. 2007, and references therein). However, this issue remains quite a matter of debate (Elmegreen 2001). Observational studies of star formation regions suggest that the IMF is set in early stages of the star’s formation process (Meyer et al. 2000; Zinnecker et al. 1993). Bound cores are potentially prestellar - the precursors to protostars, it is therefore crucial to investigate how their mass distribution varies with environment and how this compares with the stellar IMF. If gravitational fragmentation of the star forming cloud plays a dominant role (Motte et al. 1998; Beuther & Schilke 2004), would any other process such as the feedback from forming stars contribute to shaping the core mass function and consequently the IMF of the emerging cluster?

The young massive binary, AFGL 961, has been the subject of extensive studies at many wavelengths (Cohen 1973; Gullixson et al. 1983; Castelaz et al. 1985; Lenzen et al. 1984; Hodapp 1994; Aspin 1998; Li & Smith 2005). It is situated in the densest ridge of the Rosette Molecular Complex (RMC), an isolated, active massive star forming region at a distance of \( \sim 1.39 \) kpc (Hensberge et al. 2000). AFGL 961 is known to be associated with the most luminous IRAS source, IRAS 06319+0415, with an estimated luminosity of about \( 7.5 \times 10^3 \) \( L_\odot \) (Castelaz et al. 1985), in this region. High-velocity molecular gas (Blitz & Thaddeus 1980), but no sign of water masers (Engels & Lewis 1996), was detected in its surroundings. Both stars show prominent 2.166 \( \mu \)m Br-\( \gamma \) emission and there is an associated wide bipolar CO outflow preferentially oriented in the north-south direction (Lada & Gautier 1982). The signatures of strong dynamical processes (Smith et al., in preparation; Aspin 1998) and the presence of the massive protostellar system associated with AFGL 961 signifies the latest generation of massive star and cluster formation in the RMC (Li & Smith 2005; Li et al. 2008).

Thermal dust is optically thin in millimeter wavelengths up to column densities as high as \( N_{\text{H}_2} \sim 10^{25} \) cm\(^{-2}\) (Sollins & Megeath 2004) and therefore this radiation provides a key probe of the early stages of star and cluster formation. Recent single dish submillimeter observations of the AFGL 961 region at a spatial resolution of 26\" (Klein et al. 2005) have detected a strong submillimeter peak with nearly spherical morphology. They derived a total mass of 550 \( M_\odot \) and a peak number density of \( 5.0 \times 10^5 \) cm\(^{-3}\). We present initial results from the detection of a cluster of millimeter cores surrounding the young massive binary AFGL 961 based on continuum observations by the Submillimeter Array (SMA)\(^1\). The core mass distribution of this single massive protocluster is derived, which hints at how dynamic processes of newly formed massive protostars may influence the mass spectrum of the forming cluster.

2 OBSERVATIONS AND DATA REDUCTION

Observations of the AFGL 961 region\(^2\) were carried out with the SMA in the compact configuration at 230 GHz in 2005 December. Two target fields centered on AFGL 961E (R.A.=06\(^h\)34\(^m\)37.7\(^s\), Dec.=04\(^\circ\)12\('\)44.0\("\) (J2000.0)) and AFGL 961W (R.A.=06\(^h\)34\(^m\)35.7\(^s\), Dec.=04\(^\circ\)12\('\)45.0\("\) (J2000.0)), respectively, were observed. The data reduction was carried out with Miriad\(^3\). Data for QSO 3C454.3 and Uranus were used in the bandpass and flux-density calibration. QSO 0530+135 was observed for gain corrections. The continuum image for each field was constructed from the line-free channels. The primary beam is 56\" at 230 GHz, while the synthesized beam size of the continuum image with natural weighting was approximately 3.7\" \( \times \) 3.3\" (P.A.=75\(^\circ\)). The archived SMA observations of the AFGL 961 region could therefore resolve the protocluster down to physical scales of \( \sim 6000 \) AU at a distance of \( \sim 1.39 \) kpc (Hensberge et al. 2000). A simple linear mosaing algorithm was employed when mosaicing the maps of the two target fields. The primary beam attenuation was also corrected

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\(^2\) The data were retrieved from the SMA archive.

\(^3\) http://sma-www.cfa.harvard.edu/miriadWWW
in the final continuum image, which covers a field of roughly \(0.9 \text{ pc} \times 0.6 \text{ pc}\). The resultant root mean square (rms) noise level of the continuum imaging was 1.2 mJy beam\(^{-1}\).

3 RESULTS & DISCUSSION

The continuum mosaic of the SMA observations of the AFGL 961 region is shown in Figure 1 in the form of an isophotal contour map overlayed onto a color-scale image. In total, 41 clumps are detected in this observation, which are marked by Arabic numerals. All the clumps are found to be congregated within \(\sim 30''\) of this massive protostellar system. The three brightest components, AFGL 961E, W and 32, are detected and located near the phase-tracked center. The secondary bright components, 7, 8, 9, 10 and 27, 28, 29, 30, are located south and north of AFGL 961E, W and 32 respectively. The less bright clumps are predominantly distributed in the surrounding area and preferentially in the east-west direction resembling a lane like structure. The secondary bright components appear to have an approximately symmetric distribution with respect to the brightest components, and they can probably be more or less affected by sidelobes of the dirty beam due to incomplete \((u, v)\) coverage. To verify whether the secondary bright features of the north and south are caused by sidelobes, we made images of the dirty beams for AFGL 961E and AFGL 961W.

Figure 2 shows the dirty beam for the AFGL 961W field. The dirty beams are found to be exactly the same for AFGL 961E and AFGL 961W (see Fig. 2). The dirty beam is clearly seen to be dominated by the main lobe in the phase tracked center and the sidelobes are predominantly in the north-south direction. The sidelobes in the north and the south are perfectly point-symmetric both spatially and in terms of morphology. However, as presented in Figure 1, the less luminous sources we detected in the same direction are not point-symmetric, though they seem to be. Contamination from the sidelobes cannot be avoided, but can be suppressed or removed by sophisticated data processing. A common cleaning algorithm in Miriad has been used in the deconvolution, which was proven to be successful in radio interferometry by suppressing effects from the sidelobes.

As is well known, clean boxes are useful for sources with known structures. We chose a clean box around the brightest components and re-constructed the images. The noise did rise significantly in regions outside the box, however, the weak components we detected are also presented. The restored image of the AFGL 961W field is shown in Figure 3. Both the fainter components located to the north and south of the central bright ones and the weak components in the surroundings are readily seen. The detection limit of this observation is 1.2 mJy beam\(^{-1}\) and all the weak components detected have fluxes above 3 \(\sigma\). When compared with the dirty beam, the brightest components are located far to the east of the dirty beam pattern. This substantiated the true existence of the less luminous components aligned in the north-south direction. To verify the detections of the weak components, Gaussian or point models for the weak components in the \(uv\) domain were made. The same mapping processes for the entire area of Figure 1 were carried out.

Figure 4 shows an example for component 10 in Figure 1, which is clearly detected. This helps to elucidate the detection of the weak components and the \(uv\) sampling appears to be good.

Note that poor \(uv\)-sampling yields a fuzzy beam pattern and hence a blotchy appearance, in which case, the weak components cannot be revealed due to inadequate \(uv\)-sampling. This can be verified by simulating the relation between \(uv\)-sampling and the beam pattern. In this case study, the clean beam (3.7''\(\times\)3.3'', P.A. = 75') is very good. Finally, we have checked the \(uv\) coverage (see Fig. 5), in which the \(u\) and \(v\) ranges are quite similar.

Klein et al. (2005) have observed AFGL 961 at 870 \(\mu\)m using the Submillimeter Telescope (SMT) at a resolution of 26'' and found a core-halo structure (see fig. 1 of Klein et al. 2005), in which the continuum is dominated by the compact core (thick contours) with a size of 40'' and the compact core is rather spherical. In order to compare the SMA observations with the results of Klein et al. (2005), we have restored the image with a circular beam that was smoothed to a resolution of 26'' (see Fig. 6).
Fig. 1 SMA continuum imaging of the AFGL 961 region in the densest ridge of the RMC. Note that the ellipse in the lower right corner shows the synthesized beam. The contours were plotted at 3, 4, 5, 9, 13, 17, 21, 25, 29, 40, 50 and 60 times the background rms level, which corresponds to 1.2 mJy beam$^{-1}$. Sequential numbers designated at each of the millimeter cores with integrated fluxes over the 3σ detection limit are also plotted.

Fig. 2 The dirty beam we compiled with the same dataset as in our data reduction.

Figure 6 clearly shows a spherically compact core with a size similar to those in the SMT observations. The SMA is not sensitive to extended emission with scales larger than $\sim 50''$. Therefore, the SMA observations are sensitive to the clumps of high density gas rather than the extended diffuse components (e.g., the halo in fig. 1 of Klein et al. 2005). Beuther & Schilke (2004) have observed IRAS 19410+2336 at various spatial resolutions. Their results have shown spherical structures by single dish observations and multiple clumps by interferometric observations. When comparing the
SMA observations of AFGL 961 with those by Klein et al. (2005) and Beuther & Schilke (2004), it can be seen that the AFGL 961 cloud imaged by single dish observations is not uniform and contains dense clumps. Therefore the SMA observations only pick up the dense components. The observations also show that AFGL 961 has undergone fragmentation processes like in IRAS 19410+2336.

Figure 7 presents the spatial coincidence between the SMA continuum cores and our New Technology Telescope (NTT) H$_2$ 1–0 S(1) imaging of the AFGL 961 region (Smith et al., in preparation). It is evident that all the millimeter cores except those spatially coincident with the binary
Fig. 5 The uv coverage of the SMA observations as recovered in our data reduction, in which the $u$ and $v$ ranges are quite similar.

Fig. 6 The SMA data were smoothed to a resolution of 26" to facilitate comparisons with the single-dish millimeter results of the same region from Klein et al. (2005).

components of AFGL 961 show no stellar counterparts in the near infrared; this is confirmed by further comparisons with the broad band $J$, $H$ and $K_s$ imaging obtained by NTT (Smith et al., in preparation). A close investigation of archived Spitzer IRAC and MIPS 24 µm imaging data yields the same results. Remarkably, the massive cores are predominantly situated in the transverse direction of the bipolar molecular outflows (Smith et al., in preparation; Aspin 1998; Lada & Gautier 1982) associated with AFGL 961.

Figure 7 also displays the cluster of low-mass young stellar objects to the north of AFGL 961 within a fan-shaped region (Li & Smith 2005). They are spatially coincident with the approaching
lobe of the molecular outflows and were suggested to be a sign of triggered star formation. The apparent alignment of the SMA continuum emission cores in directions perpendicular to those of the outflows suggests effects of dynamical perturbations and likely a triggered origin for their formation. It is noteworthy that the exciting source of the Rosette Eye, designated as AFGL 961 II (Li & Smith 2005) and discovered by near infrared imaging of the same region (Li et al. 2008), does not show any detectable emission in the millimeter continuum. This suggests that the exciting source with at least an intermediate mass is already in a more evolved phase of its formation.

All 40 individual cores were detected above a 3σ level of the 3.6 mJy beam⁻¹. Assuming that thermal dust emission is optically thin in the millimeter range, the masses of the individual clumps were calculated following Beuther et al. (2002). Based on archived IRAS data in the far-infrared, the estimated average dust temperature around AFGL 961 is about 40 K (Li & Smith 2005). Under the assumption of a uniform dust temperature across the AFGL 961 region, core masses ranging from 0.6 to 15 M⊙ are derived. This, however, yields a lower limit of the core mass estimation as interferometric observations tend to filter out extensive dust emission. Another factor that influences the uncertainty of the mass estimation is the temperature difference between prestellar and protostellar cores, which results in an underestimation of the prestellar core mass as they usually have much lower dust temperature.

Table 1 presents the source designation, coordinates, spatial scales, orientation, peak fluxes with calculated errors from a Gaussian fit to the cores and mass estimates of the SMA continuum cores with emission above the 3σ detection limit, which corresponds to a core mass sensitivity of ~ 0.4 M⊙ at the assumed temperature of 40 K. Based on the physical scales of the individual cores, we derive a mean major axis of ~ 7000 AU for the millimeter cores. The SMA observations result in an estimate of a total mass of 107 M⊙ for the cores of the protocluster. A rough estimate for the core formation efficiency of ~ 0.19 is attained based on the total mass estimate of 550 M⊙ for the large-scale sub-mm clump encompassing the AFGL 961 region (Klein et al. 2005).
The detection of several dozen millimeter cores in the target region allows for a quantitative analysis of the differential core mass function. As compared to the Salpeter IMF with a power-law index $\alpha=2.35$ (Bonnell, Larson & Zinnecker 2007) and the core mass function in the study of other star forming regions (Motte, Andrè & Neri 1998; Beuther & Schilke 2004), a somewhat shallower slope of $1.8 \pm 0.1$ is derived from the best fit to the mass spectrum (Fig. 8).
The origin of the flatter core mass distribution could be attributed to dynamical mass segregation in the early evolutionary stages of the protocluster. However, the spatial alignment of the massive prestellar cores in specific directions around the AFGL 961 binary suggests that the massive cores have a correlated origin and have been formed locally. It is unlikely to be largely affected by dynamical mass segregation as the forming cluster is still very young (Li & Smith 2005). The limited field of this survey may well be a factor that excludes the detection of lower mass cores in the outskirts of the cluster. Alternatively, due to the effects of spatial filtering, the interferometry only picks up the dense clumps, and emission from the extended envelopes can be filtered out. This prevents the detection of less massive clumps with extensive emission and affects to some extent the slope of the derived core mass function. However, the number of less massive cores (< 10 M☉) has to be at least doubled to lead to a Salpeter like IMF in this region. Finally, we argue that the flatter core mass function is due to dynamic perturbations from the massive molecular outflows originating from the massive protostellar binary, which could have altered the otherwise more quiescent conditions of core or star formation, enhanced the formation of more massive cores and, as a result, influenced the core mass distribution in its close vicinity. The explanation considered here accounts for the spatial alignment of the massive cores along the transverse direction of the bipolar outflows of the massive binary. This is in line with a triggered origin of the massive cores. Feedback from massive young stellar objects could, therefore, be playing a major role in stimulating the gestation of new massive members and in shaping the local core mass distribution. However, the sample region in this study is comparatively small and no SMA observations of nearby fields are currently available to serve as a comparison sample; further investigations are necessary to elucidate this issue.

4 SUMMARY

The SMA observations of the AFGL 961 region in the ridge of the RMC have resulted in the detection of a cluster with at least 40 prestellar and protostellar cores. The massive cores, however,
are preferentially located near the massive molecular outflows originating from the central massive binary and seem unlikely to result from dynamical mass segregation. It is apparent that a compact cluster is forming around the massive young binary system AFGL 961. A group of faint near infrared sources has already been discovered in the fan shaped region coincident with the northern lobe of the bipolar outflows associated with AFGL 961 (Li & Smith 2005). Therefore, two major episodes of star formation are envisaged in this compact region, detailed studies of which may shed light on the initial conditions and mechanisms of star and cluster formation.

The differential core mass function is computed, which yields a somewhat shallower slope of 1.8 as compared to that of the stellar IMF. It is suggested that dynamical processes from the newly formed massive young stellar objects could have changed the initial conditions of core or star formation and enhanced the formation of more massive cores near the center of the cluster. This, in the meanwhile, cuts down the number of lower mass cores and results in the flattened mass distribution.

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