High mass star formation to the extremes: NGC 3603 at high angular resolution in the near-infrared

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Abstract.
High angular resolution observations play a decisive role for our understanding of high mass star formation processes, both within our Galaxy and in extragalactic starburst regions. We take the Galactic starburst template NGC 3603 as paradigm and report here on high angular resolution $JHK_s$ observations of the enigmatic, highly reddened sources xRS hp-r in the NGC 3603 region, which were performed with NACO at ESO’s Very Large Telescope Yepun. These broad-band imaging data strongly support the classification of xRS hp-r as high mass protostellar candidates. We also confirm unambiguously the membership of IRS 9A-C with the NGC 3603 region as gas and dust is seen to be stripped off from their circumstellar envelopes by strong stellar winds, originating from the high mass main sequence stars of the nearby OB cluster. The orientation of these gas and dust streamers coincides with that of a very faint, only marginally detected mini-pillar protruding from the adjacent molecular clump NGC 3603 MM 2. The L’ data show extended envelopes around IRS 9A-C and reveal sub-structures therein which are indicative for non-spherically distributed material. It seems obvious that protostellar mass outflows are at work to clear cavities along the polar axes of the central protostar, and/or that circumstellar disks are taking shape.

1. Introduction
One of the most fundamental, yet still unsolved problems in star formation research is addressed by the question ”How do high mass stars form?” While most details related to the formation and early evolution of low mass stars are quite well understood since almost one decade (see e.g. the PPIV review articles by [1], [20], [25], [26] and [36]), the basic processes leading to the formation of high mass stars still remain a mystery (e.g. [41], [19], and more recently [48], [22]).

There are two possible scenarios controversially discussed by theorists: First, high mass stars form by (time-variable) accretion of large amounts of gas and dust through their circumstellar envelopes and/or disks ([44], [43], [3], [5], [4], [46]). Second, high mass stars form by collision (coalescence) of protostars of lower masses ([47], [8], [6], [7]). Both scenarios bear difficulties, which impose strong constrains on the final mass of the young star. On the one hand, accretion needs to over come the radiation pressure once the young star has ignited deuterium/hydrogen burning. On the other hand, the collision model demands a dense star cluster environment to achieve a reasonably high probability for close encounters, collisions and mergers of stars.

There are three important reasons, why we know so little about the earliest phases of high mass stars. First, sites of high mass star formation are generally much more distant (several
kpc) than the nearby (<1 kpc) sites of low mass star formation. This results in a significant lack of angular resolution. Second, high mass stars evolve much faster than low mass stars. This is not only true for their (post-) main sequence evolution but also for their pre-main sequence evolution. High mass stars contract to main sequence, hydrogen burning temperatures and densities on time scales which are much shorter than typical accretion time scales ([42]). Third, as a consequence of the previous point, young high mass stars are usually deeply embedded in their natal environment (e.g. [11], [10]) and in general not detectable at optical wavelengths throughout their early phases.

Despite of these restrictions, what do we know about young high mass stars? Because they emit large amounts of hydrogen-ionizing Lyman-Continuum photons, young O type stars ionize their circumstellar material resulting in the formation of ultracompact H\(_\text{II}\) regions (UCH\(_\text{II}\)s; e.g. [17], [45], [37]). They appear as compact, luminous infrared sources and their spectral energy distributions (SEDs) show a characteristic steep increase with infrared wavelengths. For evolutionary stages prior to the UCH\(_\text{II}\) phase, the massive parental cloud cores even cause near/mid IR radiation to be entirely absorbed and re-radiated at longer (mid IR, far IR and sub-mm) wavelengths. The young objects are secluded from our views.

### 2. Motivation

Imagine that one could circumvent those high extinction values by simply blowing away most of the disturbing interstellar gas and dust which usually highly obscures the high mass protostars! At first sight, this idea might appear somewhat odd. But there is indeed a chance to lift the curtains if one investigates a scenario where young high mass stars form in the violent neighbourhood of a cluster of early type main sequence stars. The presence of already evolved O type stars provides a wealth of energetic photons as well as powerful stellar winds which are capable to evaporate and disperse the surrounding interstellar medium, setting nearby young stars free at a relatively early evolutionary stage. Such premises are given in NGC 3603 which is located at a distance of about 7 kpc in the Carina spiral arm of our Galaxy ([23], [13], [14], [33], [31]).

NGC 3603 is amongst the most luminous, optically visible H\(_\text{II}\) regions in our Galaxy, being powered by a massive star cluster which shows – together with the Arches and Quintuplet clusters close to the Galactic center ([35] and references therein) – the highest density of O and B type main sequence stars known in the Galaxy ([23], [24], [15], [16]; see Fig. 1). The hot cluster stars have a significant impact on the surrounding gas and dust, on the one hand by providing a huge amount of ionizing photons (NGC 3603’s Lyman continuum flux is \(\sim 10^{51}\) s\(^{-1}\); [18], [15]) and on the other hand by compressing and/or dispersing adjacent molecular clumps through fast stellar winds (velocities up to several 100 km s\(^{-1}\); [2]).

One of these molecular clumps (NGC 3603 MM2; [31]) is located about 1.3 towards the south of the NGC 3603 OB cluster. On the cluster facing side of this clump one finds the target of our present study, the highly reddened sources of NGC 3603 IRS9. In the framework of an extensive multi-wavelength study of NGC 3603 (for details we refer to [29], [31] and [30]) we have thoroughly characterized the brightest members of this association of extremely young high mass stellar sources, which may represent very rare examples of IR detected, high mass counterparts to low mass class 0/I protostars ([28]). To our knowledge — maybe apart from the central source(s) of the large accretion disk seen as silhouette against the bright background of the M17 H\(_\text{II}\) region ([12], [32], [27]) — there are no other high mass protostellar candidates which are caught in such early evolutionary stages, without being deeply embedded and hidden from view at near and mid IR wavelengths.

In order to further constrain the evolutionary status of NGC 3603 IRS9A–C, in particular their multiplicity and luminosity as well as their “protostellar” temperatures, we have initiated follow-up near IR imaging and spectroscopy at high angular resolution. Here we report on our
results obtained from the imaging data taken with NAOS-CONICA (NACO) at the Very Large Telescope (VLT).

3. Observations and data reduction

The NAOS-CONICA observations of NGC 3603 IRS 9A–C and their vicinity were carried out in service mode on March 25th 2003 and on April 17th 2003. NAOS-CONICA, mounted on ESO’s Very Large Telescope Yepun, consists of an Adaptive Optics (AO) based wavefront correcting system (NAOS; [40]) and a near IR imaging camera / spectrograph (CONICA; [21]). We used the 1024 × 1024 pixel array of CONICA in its 27 mas pixel scale mode, which provides an instantaneous field-of-view of 27″6 × 27″6 and allows Nyquist sampled imaging (at 2.2 μm the diffraction limit of a 8 m telescope is 57 mas). Wavefront sensing was performed with the IR sensor to close the AO loop on NGC 3603 IRS 9A (self-referencing). Strehl ratios obtained on the reference source were in the range from 7% (J) to 50% (L’).

Data were taken in the broadband filters J (λc = 1.265 μm, Δ = 0.25 μm), H (λc = 1.66 μm, Δλ = 0.33 μm), Ks (λc = 2.18 μm, Δλ = 0.35 μm) and L’ (λc = 3.80 μm, Δλ = 0.62 μm) under good and stable seeing conditions (0″7 ± 0″1 for JHKs and 0″9 ± 0″1 for L’, respectively). Detector integration times (DITs) were 10 s (J; NDIT = 3), 6 s (H; NDIT = 5), 3 s (Ks; NDIT = 10) and 0.2 s (L’; NDIT = 150). To feed the collected photons both into NAOS and CONICA we used the N20C80 dichroic for the JHKs data and the JHK dichroic for the L’ data. At all wavelengths we applied the auto-jitter technique with maximum throws of 6″. The target position (see Fig. 1) was given by NGC 3603 IRS 9A: RA_{2000} = 11^h 15^m 11.34^s, DEC_{2000} = −61° 16′ 45″ 2 and a fixed sky position was selected 3′ to its south.

Figure 1. Finding chart of NGC 3603 IRS 9 for which we used a 3-colour composite of JHKs ISAAC data ([9]). The dashed box outlines the area of our VLT + NACO study (Fig. 2).
Figure 2. 3-colour composites of our NAOS-CONICA data: JHK$_s$ (left panel) and JK$_s$L$'$ (right panel). In both panels the shown field-of-view is about 24$''$.1 × 24$''$.1, corresponding to 0.82 pc × 0.82 pc at the distance of ∼7 kpc.

Twilight flats, lamp flats and dark frames were taken through the usual NAOS-CONICA calibration plan. For each individual frame, all basic steps of data reduction (flat-fielding, sky subtraction and bad pixel correction) were performed using standard routines within the IRAF software package. For an exhaustive description of the processing of crowded field IR data we refer to [29]. For the purpose of photometric calibration the near IR standard stars S279-F (9172; J = 12.477 ± 0.009, H = 12.118 ± 0.006, K = 12.026 ± 0.006, K$_s$ = 12.031 ± 0.006; [34]) and HD 161903 (L = 6.99, L$'$ = 7.04 ± 0.01; see the UKIRT list of faint IR photometric standards) were observed. The photometry was finally performed using apertures with radii of 24 pixels (0$''$.65; J), 16 pixels (0$''$.43; H) and 12 pixels (0$''$.32; both K$_s$ and L$'$), accounting for the diverse quality of NAOS’s wavefront correction which is optimized for K$_s$ and L$'$.

4. Results and discussion
In Fig. 2 we show 3-colour representations of our J, H, K$_s$, and L$'$ data obtained with NAOS-CONICA. Each frame covers a field-of-view of 24$''$.1 × 24$''$.1, corresponding to 0.82 pc × 0.82 pc at the distance of ∼7 kpc. The colour coding is the following: J = blue, H = green and K$_s$ = red for the JHK$_s$ composite (left panel) as well as J = blue, K$_s$ = green and L$'$ = red for the JK$_s$L$'$ composite (right panel). In both panels some prominent sources and features are marked.

Through the direct comparison of the JHK$_s$ and the JK$_s$L$'$ image it is evident that the L$'$ data are extremely valuable to distinguish sources with and without infrared excess. All sources with significant infrared excess appear white / yellow / red in the JK$_s$L$'$ image. We speculate that the fainter ones may represent low luminosity / low mass stars in similar evolutionary phases as IRS9A–C. In contrast, blue colours accentuate sources without infrared excess, i.e. sources on the main sequence, which may represent either members of the NGC 3603 OB cluster or field stars in the foreground.

Our VLT + NACO imaging data leave no doubt: all three sources IRS 9A, IRS 9B and IRS 9C are unambiguously associated with the NGC 3603 region. From their extended circumstellar envelopes gas and dust is clearly seen to be stripped off towards the south-east, particularly...
Figure 3. Zooming-in on the high mass protostellar candidates of NGC 3603 IRS 9: IRS 9A (lower left), IRS 9B (upper right) and IRS 9C (lower right). All panels show 3-colour composites of the JKsL′ data.

pronounced in the case of IRS 9A and IRS 9C. These gas and dust streamers are (without applying any deprojection) roughly pointing away from the center of the nearby (the projected distance is about 2 pc; see Fig. 1) OB cluster. This leads to the conclusion that ionizing radiation and/or strong stellar winds, both originating from the high mass main sequence stars of the nearby OB cluster, are significantly interacting with the outer parts of the circumstellar envelopes, causing the ablation of gas and dust which is otherwise only weakly gravitationally bound to its central source.

The orientation of these streamers of ablated material is consistent with that of a very faint mini-pillar which is only marginally detected in our NACO data about 0.2 pc to the south of IRS 9A and which apparently protrudes from the adjacent molecular clump NGC 3603 MM 2
Figure 4. The circumstellar environment of the four sources NGC3603 IRS9A (lower left), IRS9C (lower right), IRS9B (upper right) and IRS9D (upper left; as a PSF reference for the purpose of comparison). These panels show the L' data (logarithmic scaling) after subtraction of the stellar Airy ring patterns. Contour lines are drawn at levels of 20, 30, 40, ... 90% of the peak intensity in logarithmic scaling (at levels of 35, 50, 65 and 80% in the case of IRS9D). In all panels the field-of-view is about 1.9'' x 1.9'', corresponding to 13400 AU x 13400 AU or 0.065 pc x 0.065 pc at the distance of 7 kpc. Two potential (yet unconfirmed) low luminosity companions of IRS9A are marked.

— see Fig. 1 of [28] and Fig. 8 of [31] for the distribution of the cold, dense molecular gas — towards the OB cluster, quite similar to the much larger pillars seen in Fig. 1. The presence and the extent of the molecular clump MM2 can be easily anticipated by the reduced number of stars counted in the lower left quadrant of our JHK_s and JK_sL' images (see Fig. 2). A highly reddened source close to the lower edge of the JHK_s frame is probably deeply embedded within...
As already obvious from Fig. 3, all three sources IRS9A, IRS9B and IRS9C are surrounded by envelopes of gas and dust. The circumstellar emission extends up to radii of about 1.5′ (10500 AU; IRS9A), 1.7′ (7000 AU; IRS9C) and 0.5′ (3500 AU; IRS9B). In Fig. 4 we show these envelopes after subtraction of the Airy ring patterns. The central peak of the PSF has been added again intentionally, to allow better comparison to the PSF reference source IRS9D (upper left panel) which does not show evidence for any significant circumstellar emission. Contour lines are drawn at levels of 20, 30, 40, … 90% of the peak intensity in logarithmic scaling (at levels of 35, 50, 65 and 80% in the case of IRS9D). Converted to a linear intensity scaling, these contour levels range from a fraction of a percent to 30-40% of the peak flux, indicating the faintness of the circumstellar emission relative to the central point source.

Our NAOS-CONICA L′ imaging data unambiguously reveal elongated structures within the envelopes of IRS9A–C, with typical major-to-minor axis ratios of about 2:1. The corresponding position angles of the major axis are 82° (IRS9A), 107° (IRS9B) and 90° (IRS9C). It seems that circumstellar disks, which are seen almost edge-on or under moderate inclination angles, are taking shape within the circumstellar envelopes. Simultaneously and / or complementary, the identified sub-structures within the envelopes might indicate that protostellar outflows are at work to clear cavities along the polar axes, perpendicularly to the projected disk planes. The apparently larger stand-off of the circumstellar emission from the central source on the OB cluster facing (northern) side as well as the marginal butterfly/wing-like appearance may be due to both a slight source inclination and the interaction of the circumstellar material with a wind / ionization front originating from the massive main sequence stars of the nearby star cluster. Similar effects are observed in numerical model calculations of externally illuminated and photoevaporated protostellar disks (see [38]).

These outflow and / or disk signatures can not be explained by observational artifacts as they are seen around IRS9A–C in each individual L′ frame and as they do not show up around any other source within the field-of-view of our NACO data. Moreover, the interstellar extinction law (e.g. [39]) predicts the following relations: $A_J = 0.282 A_V$, $A_H = 0.175 A_V$, $A_K = 0.112 A_V$ and $A_L = 0.058 A_V$. This means that L′ emission must be considered optically thin in comparison to the shorter near infrared or even optical wavelengths, i.e. L′ observations are well suited to probe column densities in dense gas and dust environments. With respect to the observed outflow / disk signatures within the IRS9A–C envelopes our high angular resolution L′ data thus may indeed provide reliable information along which lines-of-sight high column densities are observed. Entirely absent or relatively low L′ emission along any particular line-of-sight should then indicate areas with only small amounts of gas and dust, like in the case of piercing through an outflow cavity within a circumstellar envelope. Along the same line-of-sight the JHK$_s$ data may become optically thick before reaching the outflow cavity.

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