High-resolution studies of massive star-forming regions

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Abstract. We summarize the status of our program of near-infrared adaptive optics observations of ultracompact H\textsc{ii} regions. By means of selected results we demonstrate the usefulness of this technique for disentangling the complexity of massive star-forming regions. The primary scientific aims of our study are the identification of the ionizing stars, the characterization of the stellar population, the clarification of the role of dust for the excitation of the H\textsc{ii} region and, last but not least, the search for circumstellar disks surrounding high-mass stars. We present results obtained by adaptive optics observations and additional measurements for G45.45+0.06, G5.89-0.39, and G309.92+0.48 to illustrate our scientific objectives.

1. Introduction

With the exception of the Orion Trapezium complex, most Galactic massive star forming-regions are more distant than 1 kpc. This large average distance is one reason to apply high-angular resolution techniques for their study. The embedded massive stars give rise to ultracompact H\textsc{ii} regions (UCH\textsc{ii}s) - objects with strong emission lines and scattered radiation (e.g. Churchwell 1990). The photospheric flux of stars associated with UCH\textsc{ii}s is often overwhelmed by the nebular background, rendering their detection in seeing-limited observations difficult if not impossible. However, already diffraction-limited imaging at 4-m class telescopes effectively reduces the background contribution by more than a factor of 10 compared to conventional observations. This prompted us to apply the technique of adaptive optics (AO) for the identification of the stellar content of UCH\textsc{ii}s.

Within our program, we used the ESO ADONIS instrument (Beuzit et al. 1994) at the La Silla 3.6-m telescope and the MPIA ALFA/Omega-Cass system at the Calar Alto 3.5-m telescope (Feldt et al. 2000). ADONIS was the first
astronomical AO system which became accessible to the community. It utilizes a 256×256 NICMOS array while the ALFA/Omega-Cass camera is based on a 1k×1k HAWAII detector.

2. Target selection

The current generation of AO systems applies sensing of the wavefront reference in visible light. The need for a nearby (≤ 20") natural star is a serious constraint for the observation of massive young stellar objects which, by their nature, are deeply embedded. Therefore, we cross-correlated the USNO-2A catalog (Monet et al. 1996) with compilations of UCH\textsc{ii} and methanol maser sources (e.g. Wood & Churchwell 1989, Kurtz et al. 1994, Forster & Caswell 1998, Norris et al. 1998, Walsh et al. 1998) to identify potential targets. This led to a sample of objects where a field star is by chance close to the line of sight. The wavefront reference star has to be bright enough to yield a meaningful AO correction (Strehl ratio). In a few cases where no USNO star could be identified, we successfully tried nearby stars (e.g. G5.89-0.39, G333.6-0.22). Since the magnitudes of the wavefront reference stars were sometimes close to the limit of the AO system (V ≤ 13 mag) and, in addition, due to the decorrelation of the wavefront with increasing angle from the science target (on axis), the attainable resolution did not always reach the diffraction limit but, in any case, was superior to the seeing. At the typical distance of our targets of 3 kpc, the spatial resolution at 2.2 μm corresponds to 600 AU. Until now, we acquired data for about 30 objects, some of which, however, are more evolved H\textsc{ii} regions, like Sharpless 106 (Feldt et al. 2001).

3. Observations

Almost all sources were observed in the J, H, and K (or K’) near-infrared (NIR) bands. For some targets we obtained additional imaging using Brγ, He I, and H\textsubscript{2} narrow-band filters. A few objects were also measured polarimetrically as well as spectroscopically. Since the small pixel scale of the AO instruments leads to a rather small field of view (FOV, this holds especially for ADONIS), we tried to increase this by applying a dithering scheme, allowing the determination of the sky contribution for targets of small spatial extent.

Although we focus on our AO-NIR measurements in the present paper, supplementary data at NIR, mid-infrared (MIR) and submm/mm wavelengths have been obtained as well. Especially NIR imaging polarimetry proved to be a very useful tool for the assessment of the dust distribution and the source geometry. Furthermore, it allows to locate the primary illumination source which is generally the most massive star in the presence of a centro-symmetric polarization pattern. The 2.2 μm linear polarization maps shown here are based on observations using SOFI (Finger et al. 1998) at the ESO-NTT.
4. Results

In order to illustrate the potential of the AO technique, we present results for three sources.

4.1. G45.45+0.06

This source was among the first targets to be observed with ADONIS (Stecklum et al. 1995). Its kinematic distance is 6.6 kpc and the luminosity amounts to $1.4 \times 10^6 L_\odot$ (Wood & Churchwell 1989). The 2.2 $\mu$m image taken with SOFI is shown in Fig.1, together with the vectors of the linear polarization. At the resolution of 0\'.7, the source consists of a compact nebula with a few brightness enhancements. Quite large degrees of polarization are found in the outer areas, with almost parallel vectors. This is presumably due to scattering by foreground dust grains, aligned by the interstellar magnetic field. The foreground polarization will also disturb the appearance of a centro-symmetric pattern which is presumably the case for this object. The star at [15\''\!,10\''\!] served as wavefront reference. The deconvolved ADONIS K image is shown on the left of Fig.2 together with contours of the 6 cm radio continuum from Wood & Churchwell (1989). At the resolution of 0\''\!.15, the nebula is resolved into more than a dozen of stars, several of them arranged in a chain-like fashion along the ionization front.

In order to assess the spectral types of these stars, we estimated the extinction comparing the observed Br$\gamma$ flux to the expected one based on VLA radio continuum measurements. The dereddened H and K fluxes were used to establish the K–(H–K) color-magnitude diagram shown in Fig.2 (right). Here,
the stars are shown before and after dereddening (the gray region indicates the reddening path). It is obvious that almost all stars fall close to the upper end of the zero-age-main sequence (ZAMS), proving that they are indeed massive. The remaining scatter may arise from contributions of circumstellar extinction or infrared excess due to hot dust. Although we were able to identify the high-mass stellar population of this UCH\textsc{ii}, the limited sensitivity did not allow to study the initial mass function comprehensively, but demonstrated the presence of a cluster of massive stars. The detailed analysis of all our data and a thorough discussion of this source is given by Feldt et al. (1998).

4.2. G5.89-0.39

G5.89-0.39 is an archetype UCH\textsc{ii}, located at the distance of 2.6 kpc. Its luminosity of $3.5 \times 10^5 \, \text{L}_\odot$ requires an ionizing star of spectral type O6. The linear polarization map (Fig.3) shows a very pronounced centro-symmetric pattern, especially towards the northwest. This implies that NIR radiation can emerge into this direction rather easily, i.e. at low optical depth. Furthermore, it suggests the presence of one major illumination source, a single star or a very compact group of stars. The location of the illuminator can be estimated by minimizing the sum of the scalar product between the radius and polarization vectors through varying the position. Using polarization vectors with polarization degrees in excess of 10\% (single scattering) only, we estimated the location of the illuminator which is marked by the inclined cross. Notably, there is no visible stellar source at this position which immediately implies a large amount of extinction along this line of sight.

Fig.4 displays the ADONIS K image together with the 2 cm radio continuum contours from Wood & Churchwell (1989). While the radio morphology suggest a shell-like structure, the NIR appearance is asymmetric, with emission from the northern part only (cf. Harvey et al. 1994). We found that the IR appearance
Figure 3. K' image of G5.89-0.39 with vectors of the linear polarization. The inclined cross marks the position of the illuminator.

Figure 4. ADONIS K' image with 2 cm radio continuum contours from Wood & Churchwell (1989)
does not change from the K to the Q band, i.e. over an order of magnitude in wavelength! The lack of any IR recombination line emission from the southern part of the radio continuum region also implies a large extinction. Indeed, our 1.3 mm dust continuum map obtained with the SEST (and corrected for free-free emission) shows a dense core at this very location. Thus we conclude that the IR appearance of G5.89-0.39 is strongly affected by large column densities of foreground dust. This has been put forward by the analysis of our multi-wavelength data set (Feldt et al. 1999). Our recent ALPHA images suggest that the dust may be contained in a pillar-like structure, similar to those of M16, and that our line of sight is only slightly inclined with respect to the symmetry axis of the pillar. Thus, the direct view on the exciting star is precluded while NIR radiation can emerge and be seen in the northwest area which is not shadowed by the pillar. In this simplistic model, the radio continuum would arise from the ionized skin of the pillar and its temporal variation may reflect the change of its size due to the evaporation. However, details of this model have to be worked out yet.

4.3. G309.92+0.48

This UCH\textsuperscript{ii} belongs to the group of objects which is associated with methanol masers, thought to indicate the earliest stages of massive star formation. Moreover, the chainlike alignment of the maser spots as well as the systematic trend in radial velocity along this line led Norris et al. (1998) to suggest that the masers reside in a circumstellar disk surrounding a high-mass star. The kinematic distance of the object is 6.3 kpc and its luminosity amounts to $4.3 \times 10^5 \, L_\odot$. Fig.5 shows the 2.2 $\mu$m SOFI image with superimposed vectors of the linear polarization as well as contours of the HeI emission based on our ADONIS narrow-band imaging. For this source, two centro-symmetric patterns were found, one of them centred on the UCH\textsuperscript{ii} while the second one is caused by a less embedded star to the northwest. The location of the illuminator of the first pattern is marked by the slanted cross while the plus sign marks the reference position (center of the maser spots). Interestingly, the illuminating source does not correspond to the brightest 2.2 $\mu$m object but to a star slightly offset to the southeast with respect to the maser location which is associated with HeI emission. This proves our conjecture that the most luminous, i.e. hottest star, dominates the radiation field. Obviously, more photons emitted by this star are scattered compared to any other source in the region. We emphasize that immediately to the northwest from the reference position, there is a light area, indicating strong K band extinction presumably due to a dense clump. Thus, we conclude that the most massive star is situated very close to a dense clump, causing the ionization seen in IR recombination lines and in the radio continuum. The masers are in between the star and the dense clump, presumably in the photodissociation region. We found no evidence for a disk around the massive star. We also note that there is a slight offset between the radio continuum peak and the maser spots in the Phillips et al. (1998) data which is not consistent with the disk hypothesis. In the latter case, the radio continuum peak should always be centered on the maser spots. Furthermore, an edge-on disk as claimed by Norris et al. (1998) would cause an anisotropic radiation field, resulting in a bipolar polarization pattern (e.g. Fischer, Henning & Yorke 1994) which is not observed.
5. Conclusions

For many targets, our AO observations revealed the exciting stars of the UCHII. There is a considerable fraction of objects, however, for which large column densities preclude the NIR view of the embedded massive stars (e.g. G5.89-0.39, G9.62+0.19D). The combination of radio continuum maps and NIR images with similar beam sizes enables the determination of the intrinsic UCHII morphology. Our high-resolution imaging did not yield direct evidence for the presence of disks around massive stars which were invoked in one model of UCHIIs (Hollenbach et al. 1994). The disks might be smaller than our resolution limit or even be destroyed when the massive star becomes observable in the NIR if high-mass stars form via disks at all. In almost all cases, however, we were able to identify dense regions adjacent to the hot stars which may provide the reservoir to sustain the UCHII phase. Furthermore, it became obvious that line-of-sight effects are important for the IR appearance of UCHIIs which, in general, do not obey a simple 1D symmetry.

The next generation of AO instruments which is on the verge, e.g. the ESO system NAOS/Conica for the VLT, employs infrared wavefront detection. This will allow an unbiased survey of a large sample of UCHIIs with more than a twofold increase in spatial resolution. Instruments like this offer a great potential for the investigation how massive stars form. But like their predecessors, they will provide answers as well as questions.
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