

The Impact of Adaptive Optics on Star Formation Research

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ABSTRACT

In this paper, we discuss the benefits of ground-based, adaptive optics (AO) aided observations for star formation research. After outlining the general advantages, we present results obtained during the ALFA science demonstration programme in 1999. These results underline the absolute necessity of AO assistance for almost any kind of observations regarding star formation regions.

Keywords: Adaptive Optics, Star Formation, Initial Mass Functions, Ultracompact HII Regions, T Tauri Stars

1. INTRODUCTION

Since about 1995, when adaptive optics (AO) was broadly introduced into astronomical imaging techniques, the field of star formation has seen revolutionary progress. Why is that? The first step towards the new age had nothing to do with AO, it was the first direct imaging of circumstellar disks provided by the HST (see, e.g. McCaughrean et al.¹). Before the installation of the NICMOS instrument, however, HST had the disadvantage of being restricted to visual wavelengths. Star formation, on the other hand, usually takes place in molecular clouds. The radiation which carries information to astronomers on earth must pass through these clouds. The dust particles inside the clouds absorb most of the visual radiation, but let the infrared (IR) part and longer wavelengths pass almost untouched. Additionally, dusty structures in the immediate environment of young stellar objects (YSOs) provide IR excess emission by absorbing shorter wavelengths and re-radiating the energy in the IR. While this effectively shuts off observations of the act of star formation in the visual (and thus by the old HST), it matches excellently with the facilities provided by AO systems. Current astronomical AO systems*, as well as the very first ones 5 years ago, usually use the visible part of the electromagnetic spectrum to analyse the incoming wavefront, and provide the IR part to the science instrument. This has several reasons: First of all, it is much easier to achieve plain wavefronts at longer wavelengths: The longer the wavelength, the smaller the number of required actuators and the longer the atmospheric coherence timescale. On the other hand, using a dichroic beam splitter is more efficient than a “normal” beam splitter. AO systems with IR wavefront sensors (ADONIS at ESO now has one) or systems providing AO in the visible (like e.g. the starfire optical range), have to share photons between the wavefront analyser and the science instrument. This always imposes a further limitation on the limiting magnitudes of these systems. All these factors make AO systems ideal for observing star formation regions, apart from the fact that on large telescopes they can easily beat the resolution provided by HST. An example comparison of a typical star forming region is given in Figure 1.

Despite the HST delivering the first direct images of circumstellar disks, the detailed examination of such objects was performed later with AO systems.³ AO supported IR observations yielded information on the grain size distribution and the temperature variations inside such disks. Polarimetric studies of such disks have also been conducted.⁴ AO observations have also contributed to other fields of star formation research, like the search for brown dwarfs⁵ (Important to fill the gap between theories of star and planet formation), the identification of initial mass functions in young clusters, the phenomena of massive star formation⁶ and problems connected with binarity or multiplicity of recently formed stellar systems.

In this paper, we will present selected results obtained by a single AO system, ALFA (Adaptive Optics with a Laser for Astronomy,⁷ which is run by the two Max Planck Institutes for Astronomy and extraterrestrial physics

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*At least those available to the general, civilian community

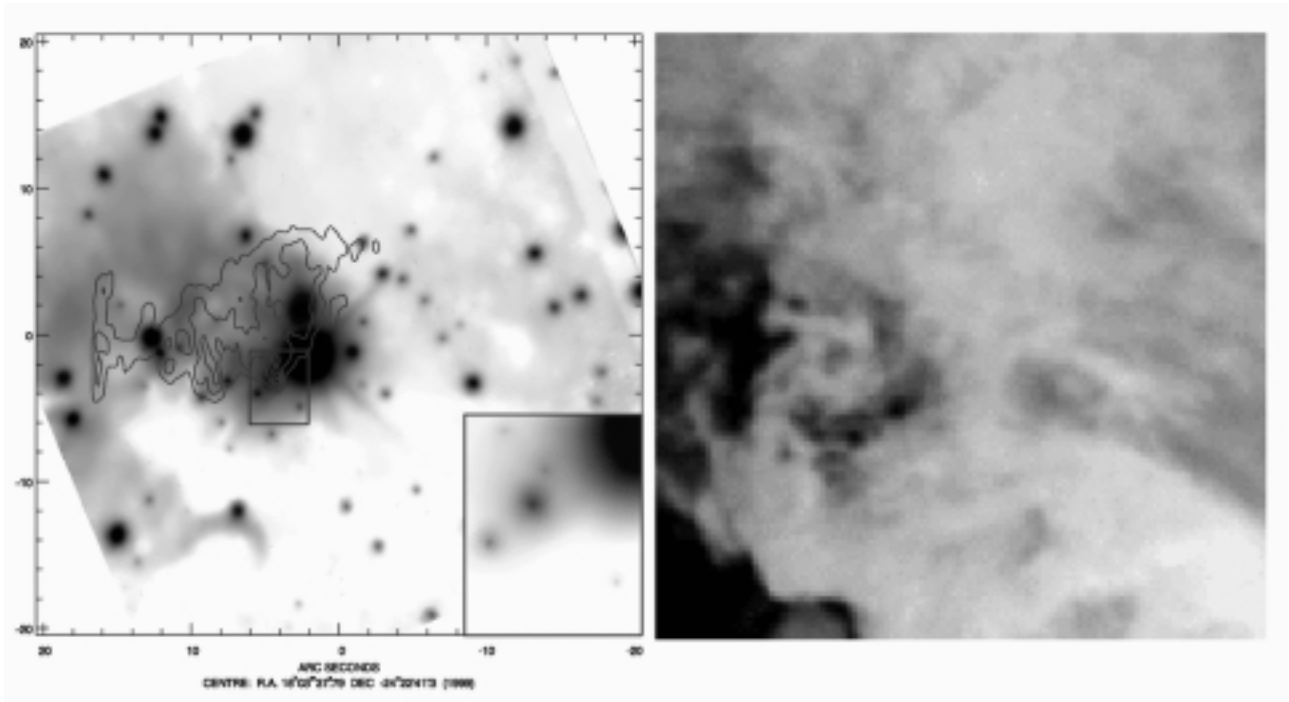


Figure 1. The core of the Lagoon Nebula. Left is an IR composite image taken with the AO system ALFA in the $J, H,$ and K' -bands. On the right, you can see the same area observed with the HST.² That is part of HST's famous "Twisters in the Lagoon" image taken with the WFPC2, do you recognise it? Note the number of obscured sources which are invisible in the HST image and the comparable resolution of the two frames.

in Heidelberg and Garching, Germany. We concentrate on fields of star formation research which are examined at the two institutes. The results we present were obtained during the ALFA science demonstration run 1999, most of them in September of that year. The intention is to give a short introduction to the fields we are working in and to present current results obtained with the ALFA system. All data presented are still under analysis and will be thoroughly presented in forthcoming papers. To provide opportunities to judge the "real life" performance of the AO system, all characteristic data (like Strehl ratios, FWHMs etc.) are given for the finally reduced data, but without any applied post-reduction techniques like deconvolution or PSF-fitting.

2. DETERMINING THE IMF OF NGC 6611

The initial mass functions (IMFs) of young clusters contain a wealth of hints towards the influence of the environment on the formation mechanisms of stars. Particularly interesting is the interaction between massive stars and their winds and ionising radiation, and low-mass stars forming in the same molecular cloud. Since the general scenario of low-mass star formation from a collapsing cloud core via a disk/outflow scenario to a protostar is more or less known,^{8,9} many parameters can be derived from the mass distribution.¹⁰ Among the questions in this context are: Does the slope of the IMF vary on small scales? Do low-mass stars in a starburst event form together with the more massive stars or at different times? It might also not be to daring to ask if low-mass stars form at all in an environment of violent, young massive stars.

2.1. Observations and Data Reduction

NGC 6611 was observed during the ALFA science demonstration run in September 1999. The seeing conditions were median with a J -band seeing of $0''.9$. Locked on the reference star of $m_V = 9.0$ the AO was running at a speed of

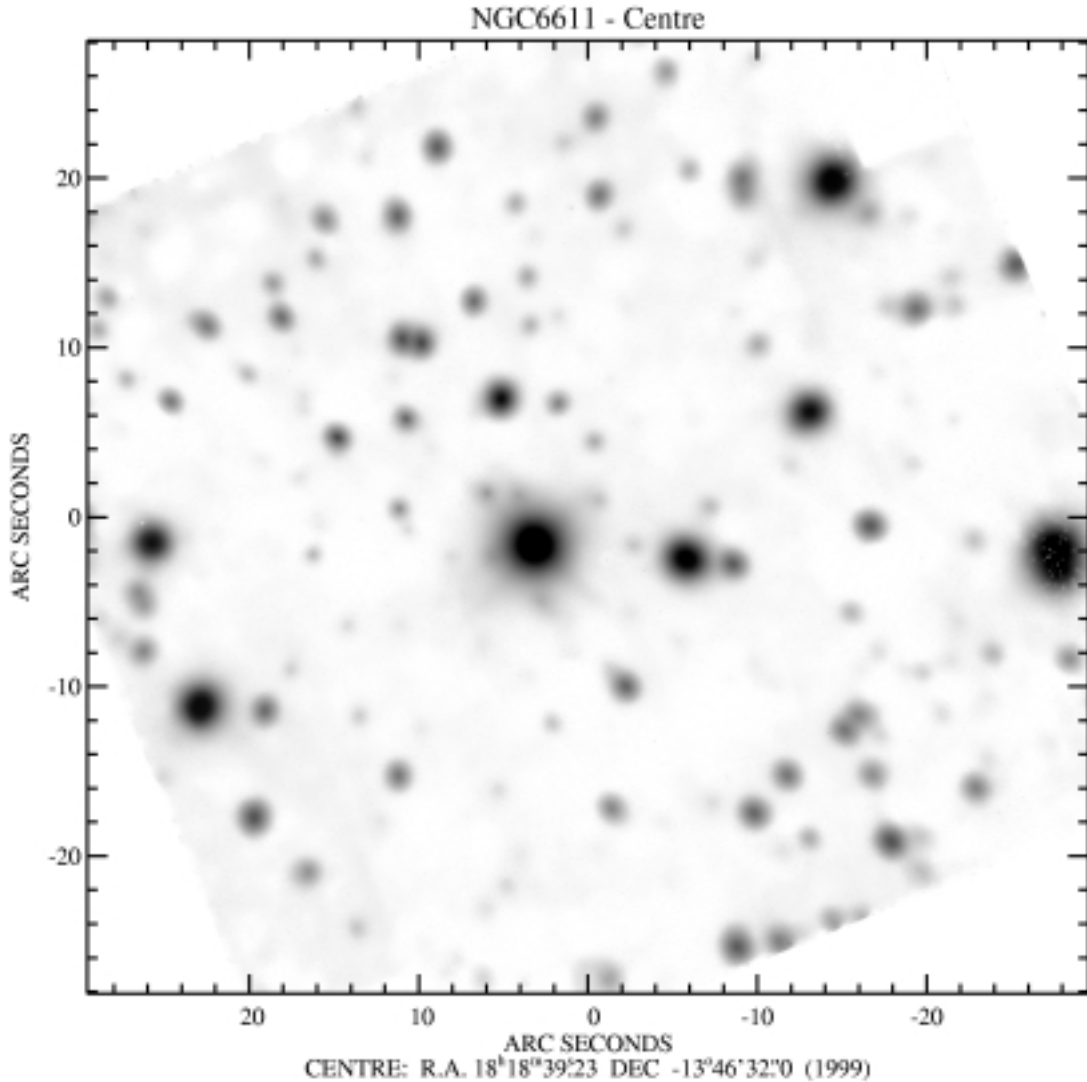


Figure 2. The core of the young cluster NGC 6611. The WFS is slightly left of the image centre, it has a brightness of 9.0 mag in V -band. Maximum Strehl in K' is 8%, the corresponding FWHM of the stellar PSF is $0''.28$. All numbers are given for the final image, which consists of images registered to each other from 5 different mosaic positions. The effect of tip-tilt anisoplanatism is clearly visible, as stars towards the edges of the image appear elongated, the major axes of their ellipses pointing towards the WFS star.

75 Hz using 18 subapertures and correcting 18 Modes[†]. Albeit, we were far from the diffraction limit (see Fig. 2). Total integration times were 5 minutes in each of the filters J , H and K' . Data reduction followed standard IR procedures, using a mosaic pattern to acquire a sky frame and subtracting that before flatfielding. Bad pixels were mostly removed during mosaic combination, few remaining bad pixels in non-overlapping regions were removed by filtering. Photometric calibration was performed by observing the standard AS37.¹² For remarks on image quality see the caption of Fig. 2

[†]We were using so-called “sensor modes”, the lower ones of which are identical to the corresponding Kahunen-Loeve modes. The upper sensor modes are linear combinations of higher KL-modes to make use of more statistically independent information than contained in the original KL-modes¹¹

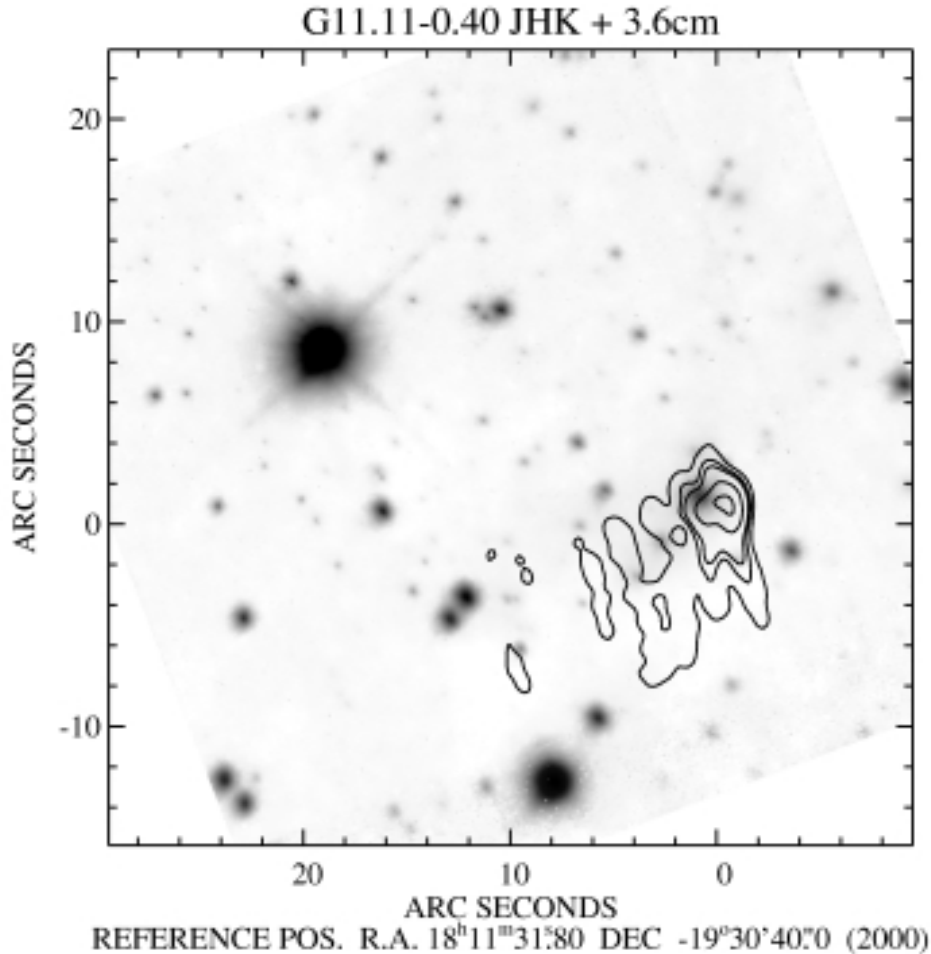


Figure 3. The UCHII G11.11-0.40. Superimposed on the JHK' colour composite (The image appears in colour in the electronic version only; please check the ALFA web page at <http://www.mpia-hd.mpg.de/ALFA>) are 3.6 cm VLA contours from KCW94. The achieved resolution on the AO reference star (WFS star) is $0''.19 / 0''.17 / 0''.24$ in $K' / H / J$. This corresponds to Strehl numbers of 17%/8%/3%. Due to the limited size of the isoplanatic patch, these values are no longer valid at the location of our target. Here, at the reference position, we reach $0''.44 / 0''.52 / 0''.55$ (2%/2%/0%). The brightness of the WFS star is 10.8 mag in V -band, the seeing during the exposure was $0''.9$

2.2. Determination of the IMF

The whole of NGC 6611 was thoroughly examined by Hillenbrand et al. (1993).¹³ They give a mean age for the cluster of $2(\pm 1) \times 10^6$ yrs and a mean extinction of 3.2 mag towards the cluster region. Relying on their age determination, we can de-redden the stars via the two-colour and the colour-magnitude diagrams. Thus we will be able to extend the IMF towards lower mass stars than Hillenbrand et al. Photometry was done using the IDL-implementation of DAOPHOT.¹⁴ The extinction towards the cluster can of course vary across the cluster and especially towards the centre - which we observed. Fig. 2 shows a distinct lack of stars close to the central WFS-star. This indication of a higher extinction towards the centre than towards the outer parts is also accompanied by indications for high reddening towards the centre (up to $A_V = 15$ mag). The process of de-reddening the sources and constructing the IMF is currently under way, the result will be published in a forthcoming paper.¹⁵

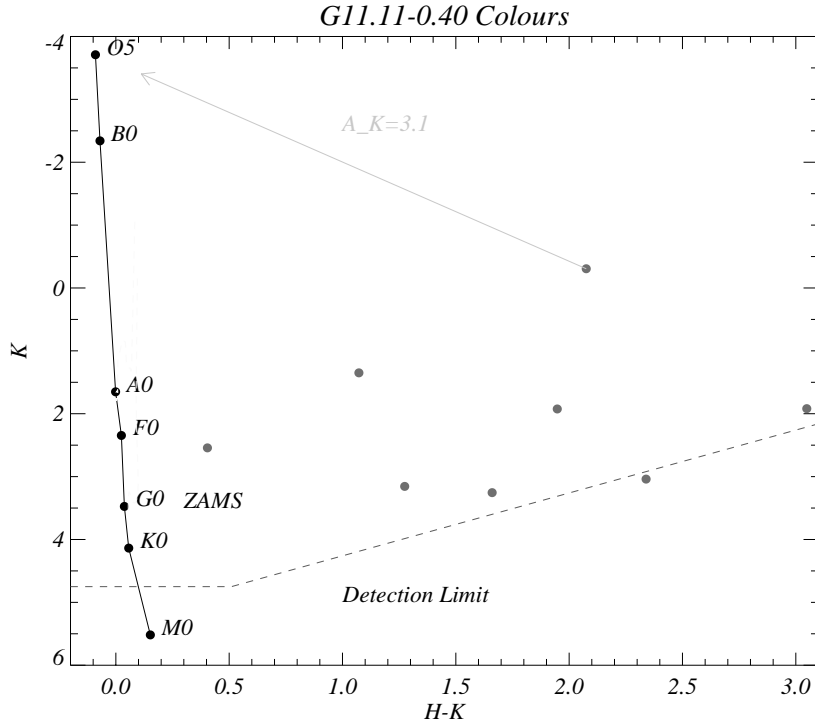


Figure 4. Colour-magnitude diagramme of G11.11-0.40. the locations of the sources in and close to the VLA map are given by the grey circles. The distance module for G11’s distance of 5.2 kpc has been applied to the magnitude values. The brightest object inside the VLA map has a dereddening arrow. This arrow gives the de-reddening vector for the extinction measured from a comparison between Br γ and 2 cm free-free flux.

3. IDENTIFYING THE IONISING SOURCE OF G11.11-0.40

Ultracompact HII regions (UCHIIs) are small (0.15 pc), ionised areas surrounding newly born massive stars ($m \geq 8 M_{\odot}$). Deeply embedded in the natal molecular clouds of these stars, UCHIIs are invisible at optical wavelengths but appear bright from the near infrared to the radio domain. UCHIIs appear in many different morphologies and one of the key questions is why they are so many of them: Comparing the lifetime which theory predicts for the expansion of an ionised shell around a star to the lifetime of O-type stars, one computes a predicted number of UCHIIs which is at least a factor of ten lower than the observed number. Among the possibilities to answer this question and to distinguish between the many models that describe UCHIIs, is the clear identification of the ionising sources of these objects.

3.1. Observations and Data Reduction

G11.11 was observed during the same night as NGC 6611. Although external conditions were practically the same and the WFS-star 2 mag fainter than that of NGC 6611, the AO system was much better adapted to the seeing this time: In the image centre, the stellar PSF is practically diffraction limited in K' and H and Strehl numbers reach 28% even after the mosaic combination. Observational parameters and techniques were also identical to NGC 6611. Total integration times were 5 minutes in each band in this case. The resulting JHK' colour composite image can be seen in Fig. 3

3.2. The Ionising Source

Figure 3 shows that clearly three rather red point sources[‡] are located close to the ionised region denoted by the contours of the 3.6 cm free-free emission. They appear to lie on the northern rim of a dark cloud which clearly blocks

[‡]At our resolution of $0''.4$

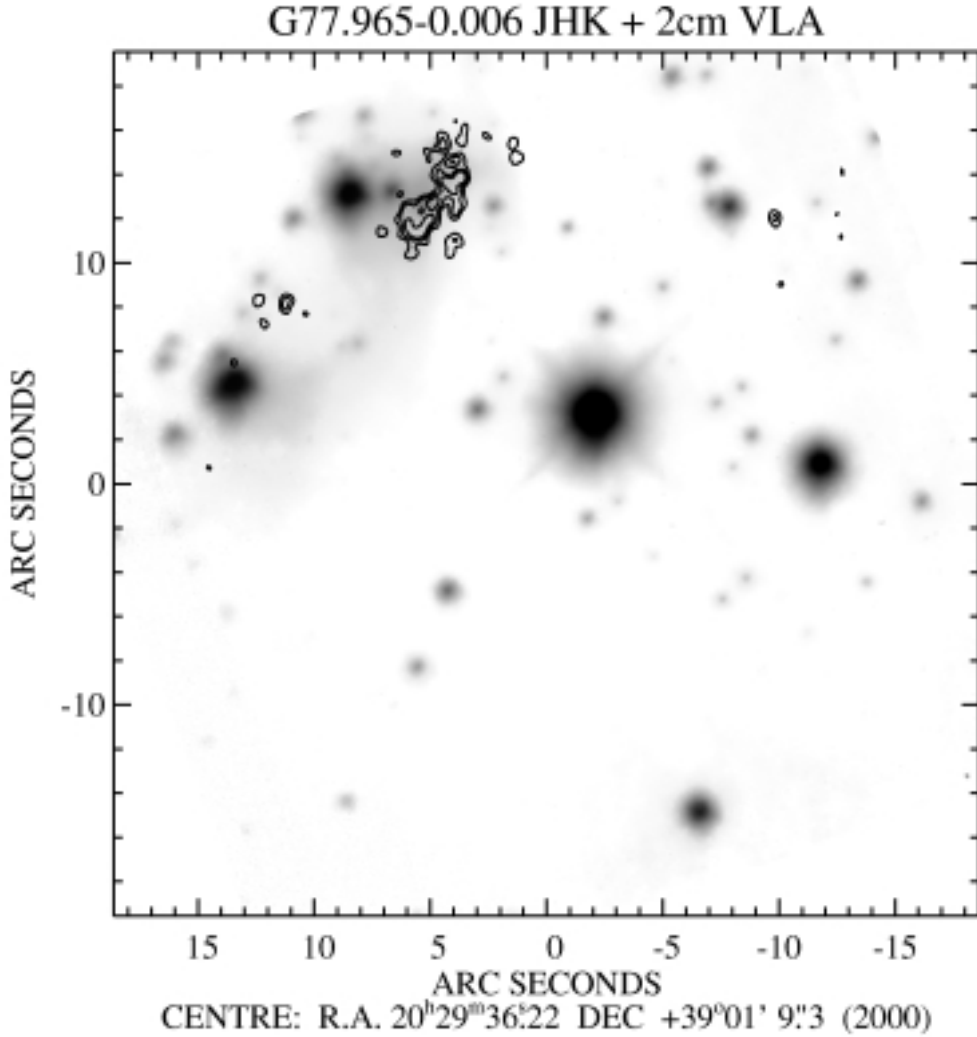


Figure 5. *JHK'* colour composite image of the UCHII G77.97-0.01 (The image appears in colour in the electronic version only). This image shows what ALFA can achieve under really limiting conditions: The seeing during the exposure was around $1''.5$ (*H*-band!) and the brightness of the WFS-star is only 11.3 mag (*V*-band). Albeit, the maximum resolutions are $0''.32 / 0''.52 / 0''.72$ in *J / H / K'* on the WFS star. This corresponds to Strehl numbers of 6%, 2%, and 0%. On the target itself, denoted by the superimposed VLA contours from KCW94, the Strehl numbers are essentially all 0, but the resolutions are still $0''.43, 0''.66, \text{ and } 0''.92$. Be reminded, that again all numbers are for the finally reduced and combined image.

background stars to the south. To identify the ionizing source of G11, photometry was performed on the *H* and *K* frames of G11. the sources inside the ionised region (see VLA contours in Fig. 3) are not detected in *J*. For photometry, an IDL adaption of DAOPHOT was used. The brightest source inside the ionised region was used as PSF reference for DAOPHOT. Since no signs for resolved additional emission was detected from this source, this step seemed justified. It also guarantees optimum adaption to the local shape of the PSF, which is slightly elongated due to tip-tilt anisoplanatism. The results of the photometry are shown in the colour-magnitude diagramme in Fig. 4. This figure shows the zero age main sequence (ZAMS) in red plus some pre-main sequence evolutionary tracks by D'Antona & Mazitelli.¹⁶ For the sources inside G11, a distance module of 13.58, corresponding to a distance of 5.2 kpc¹⁷ was applied to the *K'*-magnitude.

The 8 sources inside or closest to the ionised region are shown here. From a Br γ map observed with IRAC2b on



Figure 6. Reconstructed K' -image of T Tau taken with the 3D and ALFA instruments. The FWHM is $0''.14$, a Strehl number cannot be calculated because the total flux cannot be measured from this $1'' \times 1''$ field of view. Spectra have been extracted on the central 2×2 pixels of each PSF. The separation of the two components of the T Tau system is $0''.69$

ESO's 2.2 m telescope on La Silla (Chile), we derived the extinction towards the ionised region via comparison to the observed free-free flux at 2 cm. This procedure yielded an extinction of 3.1 mag at the wavelength of $\text{Br}\gamma$ ($2.166 \mu\text{m}$). This extinction is assumed to be constant across the K -band. When applying the corresponding de-reddening vector to the brightest source inside G11, we find the star located just short of the position of an O5 star in Fig. 4.

When calculating the Emission measure from the 2 cm emission, we get $0.7 \times 10^6 \text{ pc cm}^{-6}$, corresponding to an electron density of $4.2 \times 10^3 \text{ cm}^{-3}$. According to Kurtz et al.,¹⁷ this request a minimum $10^{47.7}$ Lyman continuum photons per second from the ionizing source. Models by Panagia¹⁸ indicate that this number can be delivered by a single star around spectral type O9. Of course one has to be careful: On the one hand, it is generally unknown how much the UV photon flux is influenced by the presumed youth of the star. On the other hand, dust inside the region may absorb Lyman continuum photons and thus require a star of earlier spectral type than O9. Such dust would, if located between the $\text{Br}\gamma$ emitting region and the star itself also explain the additional reddening between the de-reddened location of the ionizing source in Fig. 4 and the actual location of an O5 star.

Information on the other sources, on dust masses/densities and the IMF close to G11 will be given in Henning et al.¹⁹

4. SPECTROSCOPY OF THE YOUNG BINARY SYSTEM T TAU

The AO system ALFA can be operated in combination with the integral field sepectrometer 3D.²⁰ This combination was used in September 1999 to observe the young binary system T Tau. ALFA delivered a resolution of $0''.14$. Spectra were extracted from the central 2×2 pixels of each PSF. The spectral resolution of 3D is 1000 in this mode, the spectral range extends across $0.4 \mu\text{m}$ and thus across the complete H and K -bands.

4.1. The Spectra

A thorough introduction into the T Tau system can be found in Davies et al.²¹ in this volume. Resulting spectra can be seen in figures 7 and 8. The primary or northern component (N) has its maximum shortwards of the H -band and shows a falling spectral energy distribution (SED) across the K -band. These are the first clearly separated spectra of both T Tau components. The behaviour of the secondary or southern component (S) is exactly the opposite. Its

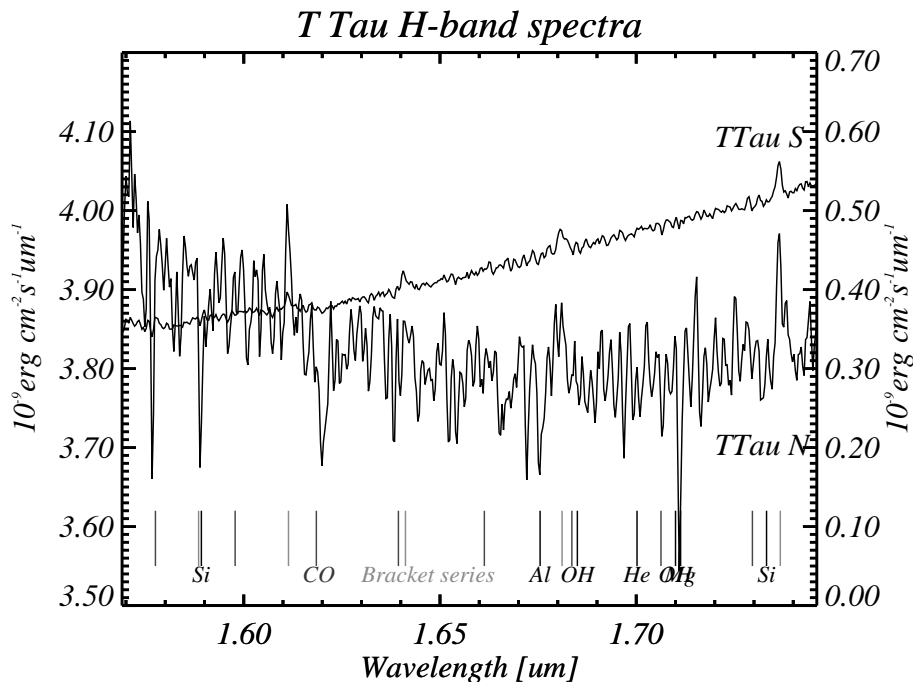


Figure 7. *H*-band spectra of the T Tau system.

SED is steeply rising across both bands. Nevertheless, the presence of pronounced Br γ lines indicates, that both objects are actively accreting, classical T Tauri stars.

As for the secondary, line emission from higher Bracket transitions can be seen in the *H*-band data. these data are currently undergoing a thorough analysis and will be presented in a forthcoming paper²²

5. THE IMPACT

We have presented data obtained during the Science demonstration programme of the ALFA system in 1999. These deal with various aspects of star formation research. The analysis of these data currently under way would have been impossible, had they been taken under seeing conditions (1'') at the time of the observations. The data quality reaches from that of corresponding to data taken at very good telescopes at very good sites (remember, we only have a 3.5 m telescope on an average mountain) to better than HST (See the spectroscopic data of T Tau). Clearly, the picture of star formation will be complemented by the detailed studies of IMFs in clusters and UCHsc iis, by the studies of ionisation mechanisms, and by highly detailed studies of individual systems like T Tau. From our results, it becomes clear that any study relying on observational results of a quality inferior to ours must lead to misleading or wrong results. Binary misidentifications, missing photometric completeness due to low sensitivity when observing with low resolutions, misinterpretations of spectral data taken in close environments of stars, all these errors are inevitable consequences of observing at natural seeing conditions of 0''.7 or worse.

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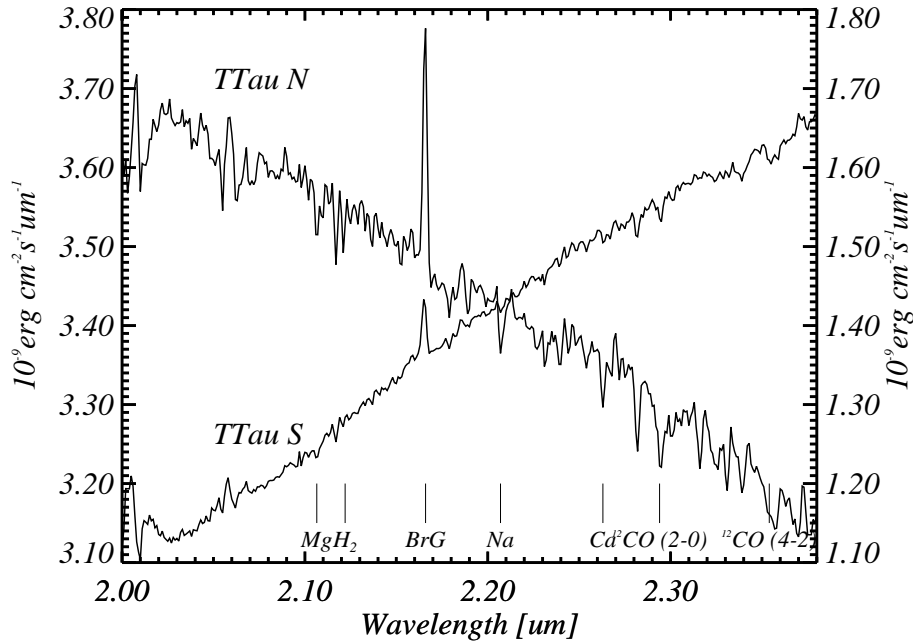


Figure 8. *K*-band spectra of the T Tau system.

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