The Initial Mass Function of the Most Massive Starforming Regions

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ABSTRACT

The stellar initial mass function (IMF) describes how many stars form at which mass. Despite recent observational progress, many fundamental properties of the IMF are still unknown. Specifically the question, whether starbursts are biased towards the formation of more massive stars, is controversially discussed in the literature. This presentation gives an overview of how the Large Binocular Telescope (LBT) will contribute to answering this question. I will present (a) the status quo of the IMF research in starbursts, (b) the importance of direct star counts in nearby templates, (c) the need for spectroscopy, (d) the advantage of the LBT over its competitors, and (e) what additional instrumentation I would like to see at the LBT for the proper investigation of the most massive starforming regions.

Keywords: Large Binocular Telescope, Stellar Initial Mass Function, HII Regions, Starformation

1. THE INITIAL MASS FUNCTION IN MASSIVE STARFORMING REGIONS

The masses of stars span at least 3 order of magnitude, from approximately 100 solar masses for the highest mass stars to the hydrogen burning limit of 0.1 solar masses. The relative numbers of stars born at a given mass is described by the initial mass function (IMF). While this distribution is of extraordinary importance for many fields in astronomy, and while a large number of investigations have addressed the topic, many properties of the IMF are still controversially discussed in the literature. The fact that scientists in the field still disagree strongly on the properties of the IMF can be illustrated by two citations from recent reviews about the IMF. Scalo (1998): “... that either the systematic uncertainties are so large that the IMF cannot yet be estimated, or that there are real and significant variations in the IMF index ...”; Kennicutt (1998): “All current observations are consistent with a single universal IMF”. Specifically, there is no consensus on the question of whether the IMF is independent of environmental conditions such as stellar density and metallicity. In other words: Is there a universal IMF?

Several recent investigations have come to different conclusions on the universality of the IMF. The strongest case for the dependence of the IMF on environmental conditions can probably be made for starbursts. These regions of extraordinarily strong star formation seem to be biased towards forming massive stars. Both indirect evidence from integrated properties of extragalactic starbursts like M82 (Rieke et al. 1993), and number counts in R 136 in 30 Doradus (Sirianni et al. 2000) indicate that these starbursts form fewer low mass stars than in the solar neighborhood. This hypothesis of a biased IMF is supported by our recent investigations of NGC 3603 (Eisenhauer et al. 1998, Brandl et al. 1999), and the HST imaging of the Arches and Quintuplet clusters (Figer et al. 1999).

Even though these clusters are several magnitudes less massive than starburst galaxies, and still a factor of 10 smaller than 30 Doradus, the IMF in these clusters has a significantly shallower power law (dN/dlogM ∝ M^{-0.7}) than the IMF in the solar neighborhood (dN/dlogM ∝ M^{-1.35}, Salpeter 1955). The heating from high mass stars, and thus the increase in the Jeans mass (Larson 1985), their radiation fields and their strong winds may lead to this deficit in low mass stars. All this evidence for a bias towards massive stars in starbursts is in contrast to the findings in the less massive galactic OB associations (Massey et al. 1995) and young starforming regions, which show an IMF similar to the field star population. However, the ionizing radiation, and thus the high mass star content, of all these optically visible clusters is by far less than what can be observed in the most massive HII regions of our Galaxy and its closest companions.

A reliable answer to the question, whether starbursts form preferentially higher mass stars, requires the direct detection of the majority of the stars in these regions. But it will be impossible in the foreseeable future to count stars with masses down to few M_{⊙} even in the closest starburst galaxies like M82 (distance 4 Mpc). We thus have to probe Galactic or Local Group templates. I will define local starburst templates as regions containing at least 100
times as many high mass stars as Orion. This is because the IMF in such massive clusters in the Galactic center and in NGC 3603 seems to be significantly shallower than for example in Orion (Hillenbrand 1997). In other words, a starburst template should contain > 100 O7 stars, or equivalently, its ionizing radiation should exceed $10^{51}$ Lyman continuum photons per second. While the large distance and the high extinction towards most giant HII regions has prevented the detailed study of the underlying stellar population in the past, the LBT will allow us to detect all stars in these clusters down to sub-solar masses.

2. FROM 4 M TELEscopes TO THE LBT: THE GALACTIC STARBURST TEMPLATE NGC 3603

NGC 3603 is the most massive optically visible HII region of the Galaxy, and as such has been the target of many studies. However, detailed studies of the stellar population of NGC 3603 were hindered by its large distance of about 7 kpc, its visual extinction of about 5 magnitudes, and its very high central concentration of about $10^5$ solar masses per cubic parsec. The central cluster of NGC 3603 can only be resolved with state of the art telescopes and instrumentation.

Optical HST imaging (Moffat et al. 1994) and ground based speckle interferometry (Hofmann et al. 1995) have been limited to the highest mass stars. But progress in adaptive optics and infrared imaging allowed us for the first time to resolve its stellar content down to stars with masses around 1 solar mass (Eisenhauer et al. 1998). These observations have been obtained at the ESO 3.6 m telescope equipped with the adaptive optics ADONIS and the SHARPII+ camera (Hofmann et al. 1993). Figure 1 shows the resulting K-band image of the central cluster of NGC 3603. While our investigations clearly excluded any turnover or truncation in the IMF down to less than 1 solar mass, these observations with a 4 m class telescope allow no analysis of the subsolar population in NGC 3603. The faintest stars detected in J-band have been only around $19^{th}$ magnitude. With the most recent imaging at the VLT we could overcome this limit by about 3 magnitudes (figure 1). We now can identify stars down to the hydrogen
burning limit in NGC 3603 (Brandl et al. 1999). But even though the observations have been carried out under excellent seeing conditions of 0.3 arcsec, severe crowding in the central regions still prevents the statistical analysis of these lowest mass stars. The need for higher angular resolution images is obvious. Only adaptive optics assisted observations at 10 m class telescopes will thus provide the answer to the question, if the IMF in starbursts is truly deficient in low mass stars compared to the “universal” field star IMF.

Such high resolution and deep infrared imaging is the unquestionable domain of the LBT. With its twin mirrors, each 8.4 m in diameter, the LBT has a light collecting area of almost 100 m$^2$. In addition, the telescope will be equipped with a high order (900 elements) adaptive optics (Salinari 2000), allowing for diffraction limited imaging at wavelengths larger 1 $\mu$m. Specifically important for its infrared performance are the adaptive secondary mirrors, so that no unnecessary thermal background is introduced by additional optical elements. Finally, the LBT will provide a coherent beam combination of both telescopes. This beam combiner will allow for interferometric imaging with a maximum baseline of 23 m over a field as large as arcminutes (Herbst 2000). The implications for deep infrared imaging are twofold: The LBT will image 10 times fainter objects than a 4 m class telescope, pushing the limiting magnitude in K-band below 23rd magnitude. The spatial resolution at this wavelength will be better than 50 mas. We can expect to find stars with 20%-40% of the mass as those seen with a 4 m class telescope (assuming $L \propto M^{1.5-2.5}$ for pre-main-sequence stars), and 3-8 times more stars (assuming a Salpeter IMF with $N(Mass < M) \propto M^{-1.35}$). Without suffering from crowding as in our seeing limited VLT observations of NGC 3603, we would be able to detect all stars in NGC 3603 down to the hydrogen burning limit, and could draw a reliable IMF in this cluster down to less than 0.1 solar masses.

3. HIDDEN GALACTIC STARBURSTS AND EXTRAGALACTIC HII REGION

While NGC 3603 is one of the best examples to outline the scientific driver for the determination of the IMF in starburst templates and to highlight the advantage of the LBT over present telescopes, this cluster (declination -61°) can unfortunately not be observed from Mount Graham (latitude 33°).

However, NGC 3603 is only one out of about a dozen clusters in the Galaxy, which fulfill my criteria of a starburst template, having 100 times as many high mass stars as Orion. A sample of such giant HII regions can be drawn using their total ionizing flux observed at radio wavelengths (Georgelin & Georgelin 1976, Smith et al. 1978). Amongst the most massive HII regions observable from the northern Hemisphere are W41, W42, W43, W49 and W51. Several of these regions have been the target of previous investigations (Blum et al. 1999, 2000, Goldader & Wynn-Williams 1994), but to date, the high extinction towards these regions and the high stellar concentration have prevented the determination of the IMF for low mass stars with 4 m telescopes.

In addition to these galactic starburst clusters, the LBT will also allow the detailed analysis of extragalactic HII regions. While the Magellanic Clouds are the domain of southern telescopes, the two nearest spiral galaxies M31 and M33 are observable from Mount Graham. Both galaxies exhibit a number of giant HII regions — NGC 206 in M31, and NGC 595 and NGC 604 in M33 being the most prominent examples — and the stellar populations in these regions have been investigated by several HST and ground based observations (Hunter & Winkelman 1999, Malumuth et al. 1996, Drissen et al. 1993). However, these observations have been limited to visible wavelengths, and maybe a significant fraction of newly formed stars and even the real cluster center are hidden behind several magnitudes of extinction. Deep high resolution infrared imaging with the LBT will thus provide more reliable measurements of the IMF in these extragalactic HII regions.

4. THE NEED FOR SPECTROSCOPY

Many measurements of the IMF in star clusters have been based solely on photometry so far. By comparing multi-color information with the theoretical stellar evolutionary tracks of post- and pre-main-sequence stars (Meynet et al. 1994, D’Antona & Mazzitelli 1994), one can derive the age of the stellar population, and then convert the measured luminosities to stellar masses. Under the best circumstances, one can even assign an individual age and extinction to the stars.

But specifically for the highest and lowest mass stars of young clusters, this photometric mass determination is affected by large uncertainties: for example, the evolution in the Hertzsprung-Russel diagram is not single valued for stars with several tens of solar masses. In addition, their evolutionary tracks depend highly on individual properties like metallicity and mass loss rate, which are not a priori known for the stellar population. Specifically, the mass loss
rate can vary strongly from star to star. The situation for low mass stars in their early pre-main-sequence evolution is no better. Still partially hidden in their dust cocoons, the extinction can vary dramatically from one star to the next. These stars also exhibit strong excess emission from surrounding accretion disks, which adds significantly to the total flux in the infrared. We therefore require spectroscopy for the proper mass determination of the high and low mass stars in the young starforming regions. But optical spectroscopy for the stars in many starburst regions is prevented by the high extinction, and we have to restrict ourselves to infrared wavelengths.

Near infrared spectroscopy can indeed provide the diagnostic tools. Given sufficient spectral resolution of 2000 and a signal to noise ratio of 30, derived stellar parameters such as mass-loss rate, luminosity, surface abundance and temperature show good agreement between optical and near infrared spectral analysis of high mass Of and WNL stars (Bohannan & Crowther 1999). The effective temperature of low-mass-stars can be determined to approximately ±300 K from several spectral features (e.g. CaI, NaI, $^{12}$CO(2,0)) in the K-band, which vary significantly with temperature (Ali et al. 1995). The spectral resolution in the analysis of Ali et al. (1995) was approximately 1400.

This need for advanced spectroscopic capabilities brings me to my wish-list for additional instrumentation for the LBT.

5. ADDITIONAL INSTRUMENTATION FOR THE LBT

An accurate measurement of the initial mass function from direct star counts requires infrared imaging and spectroscopy of several hundred to thousand stars at the highest angular resolution. The LBT with its high order adaptive optics provides the basis for such investigations.

However, almost all giant galactic starforming regions are hidden behind so many magnitudes of extinction that no sufficiently bright reference star is within the isoplanatic patch to correct for atmospheric aberrations using adaptive optics. There are two possible techniques to overcome this problem. The first possibility is the installation of a laser guide star facility, which effectively will provide full sky coverage. Such a facility was integrated and tested for example at the Calar Alto Observatory (Eckart et al. 2000). The second possibility would be the implementation of an infrared wave front sensor. While such a wave front sensor is only of minor help for extragalactic astronomy, the hidden galactic clusters have sufficiently bright stars to be used as a wave front reference in the infrared. Such an infrared wave front sensor is presently implemented in the adaptive optics at the VLT (Rousset et al. 1998).

In terms of its spectroscopic capabilities, the first generation of instruments at the LBT is not well suited for our purpose. The near infrared camera and spectrometer LUCIFER (Mandel 2000) will provide multi-object spectroscopy only for seeing limited observations. The use of its integral field unit or of a long slit will not allow the spectroscopy of several hundred to thousand stars in crowded fields. Such a detailed analysis of the stellar population in starbursts will require a cryogenic multi-object spectrograph working at the diffraction limit of the LBT.

In summary, I would like to see a laser guide star facility or an infrared wave front sensor, and a diffraction limited multi-object spectrograph at the LBT as soon as possible.

6. SUMMARY

The most massive star forming regions in our Galaxy and in the nearby spirals M31 and M33 are prime targets for a direct measurement of the IMF. These observations will provide a reliable test of hypothesis that the IMF is biased towards massive stars in starburst, and will thus give convincing evidence for or against a universal IMF. Optimized for infrared observations, providing a large collecting area, and equipped with a high order adaptive optics, the LBT will contribute significantly to the measurement of the IMF in these dense and distant clusters. However, a laser guide star facility or an infrared wave front sensor, and a diffraction limited multi-object spectrograph should be installed at the LBT, to allow for the observation of hidden clusters and more reliable mass estimates for the individual stars.

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