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STELLAR CONTENT OF RESOLVED STARBURSTS

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RESUMEN

Se discuten la estructura y contenido estelar de los cúmulos ionizantes y masivos en el Grupo Local. Las evidencias actuales indican que la función inicial de masa (IMF) es *universal*, independiente de los factores ambientales. Puede describirse por una ley de potencias con un exponente *único*, $\Gamma \simeq -1.0$ (Salpeter $= -1.35$) desde $\sim 100\ M_\odot$ hasta $\sim 1 M_\odot$, y posiblemente hasta mas allá de $\sim 0.1\ M_\odot$. La IMF está posiblemente conectada al espectro turbulento de masas de nubes moleculares.

ABSTRACT

This paper deals with the stellar content and structure of massive ionizing clusters in the Local Group. In particular, current evidence favour a *universal* initial mass function (IMF), independent of environmental factors, that can be expressed by a *single* power-law of slope $\Gamma \simeq -1.0$ (Salpeter $= -1.35$) from $\sim 100\ M_\odot$ down to $\sim 1\ M_\odot$ and possibly even $\sim 0.1\ M_\odot$ or further. The stellar IMF is connected, possibly in a simple way, to the universal power-law turbulent mass-spectrum seen over at least six orders of magnitude in molecular clouds.

Key words: **GALAXIES: STARBURST — STARS: MASS FUNCTION — TURBULENCE**

1. NEED FOR PROBING THE DETAILED STELLAR CONTENT IN STARBURSTS

R. Terlevich (this volume) has proposed a clear definition of what one means by a "starburst galaxy": a galaxy in which most of the radiation arises in active starbursts. On the other hand, dropping the word "galaxy" gives one the liberty to consider a starburst *per se* as a region of intense star formation, varying in principal anywhere from a small stellar group to a whole galaxy. This has the advantage that it allows one to make the necessary connection, if any, between relatively nearby (thus generally less massive), resolved starbursts, and more distant (normally more massive), unresolved starbursts. This paper deals primarily with the former, whose utility can probably best be summarized in the following three ways:

- Extracting the basic parameters (age and its spread, shape of the IMF, metallicity) of distant, unresolved starbursts, which are becoming more and more relevant and exciting in a cosmological context, can be a hazardous process. Coupling of the effects of some of these parameters, combined with non-perfect (i.e., real!) data and the stochastic nature of star formation, can easily lead to non-unique, even wildly deviant solutions (e.g., Leitherer 1996). Therefore, one *must* attempt to calibrate or constrain such difficult regions by studying at least some of their *nearby* cousins, where one can obtain a spectrum and photometry of each individual star, and thus determine these parameters unambiguously (e.g., for 30 Dor: Vacca et al. 1995).
- A by-product of studying nearby, resolved starbursts, is that in the case of the most massive ones, one has a *statistically viable* sample of stars that will serve well to constrain the theory of stellar evolution. This is especially critical for the most massive stars, where there are still numerous uncertainties (e.g., Maeder 1996).
- Resolution into individual stars also allows one to better study the kinematics, dynamics and structure of dense, active star-forming regions. This *can* be done by probing the light distribution (as opposed to counting individual stars), but often with misleading, ambiguous results (e.g., the Galactic centre cluster: Eckart et al. 1993; or the Galactic Giant H II Region NGC 3603: Moffat et al. 1994a).

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2. KEY QUESTION

An unresolved question that has been around a long time is whether the initial mass function (IMF) depends on environment, and if so, how. Normally, the IMF is expressed (at least over some restricted, finite mass-interval) by a power-law:

$$dN(M) \sim N(M)dM \sim M^{\gamma}dM, \text{ or}$$

$$dN(logM) \sim N(logM)d(logM) \sim M^{\Gamma}d(logM),$$

in which $\gamma = \Gamma - 1$. The widely referred-to reference-exponent of Salpeter (1955), based on nearby Galactic field stars of mass in the range $\sim 0.4 - 10\ M_{\odot}$, is $\gamma = -2.35$ or $\Gamma = -1.35$. In this context, the question boils down to determining if and how Γ, as well as the upper and lower limits of star formation, M_u, M_l, depend on key environmental parameters such as metallicity, density, and total mass.

3. PROBLEMS

The overall study of starbursts is plagued by several, often severe problems:

- Selection effects: because of their rarity, larger (more exotic) starbursts tend to be found at larger distances, as a consequence of the negative power law distribution of starburst total luminosities (e.g., Ho, these proceedings): $N(L) \sim L^{-2}dL$. A further complication is that distant objects often contain knots with luminosities exceeding even that of 30 Dor. These may be predecessors of globular clusters.
- Inhomogeneity: starbursts show a wide range of size and density, from very loose (often containing knots; e.g., NGC 604 in M33) to extremely tight (small, dense; e.g., R136 at the core of 30 Dor in the LMC). With a resolution of 0.1", *HST* can resolve individual stars in the former to as far as ~ 5 Mpc, but in the latter to only ~ 0.05 Mpc (i.e., LMC).
- Gradients: within more extended starbursts, one must be aware of the possibility of age and metallicity gradients. If not allowed for, this will complicate and could even falsify the interpretation.
- Uncertainties in stellar evolution theory: the extraction of ages requires an accurate theory of interpretation in the colour-magnitude diagram. Presently, this is plagued still by serious uncertainties, especially for the more massive stars, in the masses, mass-loss rates, overshooting and internal mixing. This is especially problematic for the youngest, most luminous regions (especially interesting in the context of distant starbursts).

4. SOLUTION

Clearly, in order to find out what parameters affect starbursts, one needs to study the detailed stellar content of a wide variety of nearby starbursts, ranging over size, density, age and metallicity. This is a difficult task, and we will be content for the time being to look first at a few extreme cases, limited to the Local Group, where spatial resolution is tractable in most cases.

In the Galaxy, many studies are available for low to medium density, young star clusters and associations of various ages and a modest range in metallicity. These include familiar regions like the Orion Nebula and the η Carinae Nebula. On the extreme high-density end of the scale, one has the Galactic centre cluster and NGC 3603. The former is likely a mixture of different populations of various ages, while the latter appears to be a truly instantaneous starburst, of particular importance.

Beyond our Galaxy, numerous young clusters abound in the Magellanic Clouds, culminating in the extreme regions of 30 Dor in the LMC, with its very dense nucleus R136, and NGC 346 in the SMC. Increasing the distance by another order of magnitude, one arrives at M33 with its relatively loose Giant H II Regions (GHR), of which NGC 604 and 595 are the most massive. Other starbursts exist elsewhere in the Local Group, but they are nowhere near as dense or massive as the above. In particular, M31 is poor in GHRs. One notes already in the LG the trend of increasing star formation activity as one progresses to later type spiral and irregular galaxies.

In the rest of this paper we will emphasize recent high spatial resolution photometry and spectroscopy obtained with *HST* of the very high density regions NGC 3603 and R136, but always in the broader context of star-forming regions of various dimensions.

As an aside, let us note that Wolf-Rayet stars play an especially important role in young starbursts with instantaneous burst ages in the range 3-6 years. WR stars are the evolved descendants of stars with initial masses above some 25 $M_{\odot}$ for Solar metallicity, increasing as the metallicity (thus opacity-driving in stellar winds) diminishes. WR stars have very strong emission lines, which makes them easy to pick out *individually*, even in relatively dense fields. The number ratio of WR- to O-stars ranges up to about 0.1 for instantaneous starbursts with ages of 3-6 Myr, decreasing for sub-solar metallicity to 0.01 for $Z_\odot/10$, in a much narrower window of barely 3-4 Myr (e.g., Arnault et al. 1989). The number ratio of WC to WN stars also decreases with decreasing metallicity.

5. RESULTS

We discuss now the questions of the IMF, C-M diagrams and structure of the stellar component of nearby starbursts. Note that most of these results are still in flux, and I will allow myself some degree of "intuitive speculation".

5.1. IMF

I will restrict the discussion here to the *form* of the initial mass function, idealized by a slope, along with an upper and a lower mass-limit. Although important in the context of star-formation efficiency, I will not consider here the overall number of stars in the burst.

Probably the most obvious and secure constraint on the IMF concerns M_u. For some years now, it has become clear that the upper limit of star formation in galaxies is probably close to 100 $M_\odot$, give or take a few 10 $M_\odot$. This is reflected in the C-M diagrams for luminous stars in fairly complete samples, like the Galaxy, LMC and SMC (e.g., Humphreys 1986), where an upper envelope prevails, known as the "Humphreys-Davidson" limit. This envelope corresponds to the Eddington luminosity and is determined mainly by the photospheric opacity of the star. When stars evolve off the main sequence, they move to lower surface temperatures (and thus higher opacities) and encounter this limit (which is closer to the ZAMS for higher masses, where the ultimate limit of star formation is close to $\sim$ 100 $M_\odot$), thereby becoming highly unstable in a so-called "Luminous Blue Variable" stage, losing large amounts of mass before moving back to the blue, eventually to become (probably after several oscillations across the limit) a Wolf-Rayet star. No stars are stable enough to exist above the H-D limit, which does not appear to depend on any obvious external parameters, such as metallicity or density. This is indeed quite curious, since if the H-D limit is opacity limited, why does not metallicity play a role? (Perhaps the answer is that it does, but with the present data, the role is mild and not obvious.) Claims for real variations in M_u must therefore be taken with great caution, as age effects related to stellar evolution, as well as small-number statistics, can simulate an apparent low value of M_u.

As far as M_l is concerned, I think there are still far too many biases and selection effects to be able to say seriously whether such a true limit (above Jupiter-like masses) exists anywhere. Claims have been made for values in the range 1-10 $M_\odot$ in some extreme starburst regions, based on observation of *global* parameters, such as H-β emission flux, combined with starlight. On the other hand, present-day old globular clusters in the Galaxy, which must have been spectacular starbursts at one time, do have large numbers of faint, low-mass stars, implying that their original M_l must have been small, well below 1 $M_\odot$ and possible even 0.1 $M_\odot$. Another problem is that in young starbursts, the low-mass stars are still contracting onto the main sequence, making their detection for very low masses difficult with classical techniques. New deep, high-resolution IR imagery may eventually settle this, once the theoretical conversion of luminosity into mass becomes reliable.

Between these two limits, one often characterizes the IMF by a slope, as noted above. The slope need not be constant; it could depend on the mass itself, as claimed by Miller & Scalo (1979), although considerably revised later (Scalo 1986). However, let us look in more detail at more recent determinations of the IMF based on photometric and spectroscopic data in the Galaxy, the Magellanic Clouds, and M33.

The most reliable, systematic work on young clusters and associations is probably that of Massey et al. (1991, 1993, 1995a, 1995b) from extensive ground based data, and Hunter et al. (1995, 1996a, 1996b) from *HST* data, for stars of mass above $\sim 5-10$ $M_\odot$. The trend emerging from these data sets (and others) is quite clear: values of Γ lie mostly in the range -1.0 to -1.3, with typical uncertainties of about 0.1 to 0.2 per value. There is no correlation with metallicity (from solar to 1/10 solar), ambient density, or total mass of the region. Massey et al. (1995a) note that the IMF slope Γ tends to be more negative (larger in the absolute sense) when the determination is based on photometry alone, than when (more reliably!) both photometry and spectroscopy are used together. Therefore, there may be some preference for values of Γ closer to unity than the original Salpeter (1955) slope ($\Gamma = -1.35$) based on field stars of masses 0.4-10 $M_\odot$ in the solar neighbourhood. Indeed, H. Zinnecker (priv. comm.) has recalculated Salpeter's slope using the same data, but adopting a more realistic age of the Galactic disk of 12 Myr, instead of 6 Myr assumed by Salpeter. Zinnecker finds $\Gamma = -1.05$ instead of -1.35.

On the other hand, Massey et al. (1995a) find much steeper slopes for massive stars in the *field* for the Galaxy and the Magellanic Clouds: Γ(field) ~ -4. This is quite surprising, since they find no correlation of Γ with size or density of the cluster/association. Why should the field suddenly "jump" to a much steeper slope? Several reasons come to mind: some massive stars in the field may be the result of mass-dependent ejection from clusters, and hence not reflect a true IMF; the field statistics are much poorer than for the clusters; the field contains a very inhomogeneous mixture of ages, the correction for which requires (still uncertain) theory; and corrections for incompleteness are rather large. In short, the final slope for the field depends on few independent data points, so that systematic errors, which are difficult to estimate, may be significantly larger than the internal errors quoted for the precision of Γ (field). In any case, with regard to starbursts, which are often taken to be an extreme case of star cluster, we need not be too concerned with the field.

What can be said about lower mass stars? Recently, Kroupa (1995) has estimated values of Γ for the nearby Galactic disk, varying from -1.7 for M above 1.0 $M_\odot$, -1.2 for $M = 0.5 - 1.0$ $M_\odot$ and -0.3 for $M = 0.08 - 0.5$ $M_\odot$. Even more recent work of Mera et al. (1996), with a new improved conversion of luminosity to mass, finds $\Gamma = -1.0 \pm 0.5$ for $M < 0.6$ $M_\odot$ for the Galactic disk. The steeper value of Γ compared to previous slopes is partly due to better treatment of unresolved binaries, in both cases. This latter work would suggest that there may be a significant number of brown dwarfs, a result which is still controversial (e.g., Williams et al. 1996).

For population II IMFs, there is also still a problem in converting luminosity to mass, as current stellar models still do not fit the lower main sequence very well. There is also the problem of accounting for the dynamical loss of low-mass stars from globular clusters. In any case, it does appear that the IMF slopes are most likely somewhat less steep than the Salpeter value (H.B. Richer, priv. comm.), and may be close to $\Gamma = -1$ or $\gamma = -2$.

In summary for the IMF, it seems that the best we can say at present is that *stars seem to form in nearly the same way, independent of environmental factors, possibly with a unique power law slope* $\Gamma = -1$ *for stars downwards of* ~ 100 $M_\odot$ *to* ~ 1 $M_\odot$, *and maybe even* ~ 0.1 $M_\odot$ *and lower.* If such a universal power law really exists for stars, the question begs whether this is related to the known power-law turbulent mass-spectrum of the molecular clouds that form stars. Elmegreen (1993) has discussed the existence of such a possible connection between scaling laws in molecular clouds and the IMF of stars. Inspired by his (more complicated) work, I propose a very simple connection. Assume first that CO molecular cloud observations (with universal mass-spectrum observed over many (at least 6) orders of magnitude in mass: $dN_{CO}(M) \sim M^{-1.7}dM$: e.g., Stutzki 1993) represent a sort of "snapshot" in time of the hierarchical cloudlet structures. Then, assume that all stars of different mass form from such cloudlets over the same finite time interval, Δt (cf., Stahler 1985). With lifetime $\tau(M)$ of cloudlets of mass M, the expected stellar mass function might then be:

$$dN_*(M) \sim N_{CO}(M)dM\Delta t/\tau(M),$$

assuming $1/\tau(M)$ reflects the *creation* frequency per unit time of stars of mass M during the formation interval Δt. Of course, this condition completely neglects all the complex physics that must be going on (e.g., Adams & Fatuzzo 1996: winds, accretion disks, etc...); it simply reflects the fact that the fractal structure of compressible turbulence in the proto-molecular cloud is breaking up and re-forming all the time, in such a way that the lifetimes of the various structures depend on average on their current size (or mass). In fact, turbulence, as reflected by the scaling laws of energy cascading to the dissipation level, *is* a way of allowing for a balance between coagulation and fragmentation, concepts often encountered in the context of star formation. To derive the mass dependence of $\tau(M)$, we use the scaling model of Larson (1981):

$$\tau \equiv l/\sigma_v = (G\rho)^{-1/2}; \rho\sigma_v^2 = constant,$$

from virial equilibrium and from pressure equilibrium in a compressible medium, respectively, where $\rho(\sim M/l^3)$ is the density and σ_v is the velocity dispersion of an elementary vortex of size l. This leads to $\tau \sim l^{1/2}, \rho \sim 1/l$, and thus $M \sim \rho l^3 \sim l^2 \sim \tau^4$, and finally the stellar IMF:

$$dN_*(M) \sim M^{-1.7-1/4}dM \sim M^{-1.95}dM,$$

which is very similar to the observed universal value, with exponent near $\gamma = -2.0(\Gamma = -1.0)$.

This is not a proof that this is the correct model! However, one fact does seem inescapable: star formation must be intimately related to the turbulent conditions in the (molecular) gas that preceded it. The actual stellar mass-spectrum is thus a consequence of the nature of supersonic turbulence in a compressible medium. In fact, even if the physics (e.g., the turbulent driver, or the type of medium) is different, the result is always nearly the same, which gives some comfort with regards to the observed universal nature of CO cloud clumping and the IMF (but little comfort if one wants to say something about the *nature* of the turbulent medium!). To give

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a concrete example of another context of astrophysical turbulence, I note the recent discovery of clumping and CO-like scaling laws in hot-star winds (Moffat et al. 1994b), where the dominant driver is probably radiation pressure (as opposed to gravity or magnetism), and the medium is highly ionized atomic (not cool molecular).

5.2. Color-Magnitude Diagrams

Now that *HST* is functioning in its full resolution potential, one can test whether the nearby extreme starbursts R136 and NGC 3603 in fact show normal stellar evolution, on the basis of their CMDs. The photometric study of R136 by Hunter et al. (1995, 1996a) and the spectroscopic/(photometric) study of NGC 3603 by Moffat et al. (1994a) and Drissen et al. (1995) show this indeed to be the case. I.e., ambient density and total mass appear to have no effect on the appearance of the CMD, for a given age. If anything, the CMDs of these tight objects may also be tighter, with a much larger sample of stars to work with.

In particular, NGC 3603, which is 7 times closer than, but intrinsically at least as dense as R136, contains at least a dozen spectroscopically confirmed O3 stars in a volume of radius $\sim$ 1 pc (Moffat et al., in preparation). It is therefore the largest and densest concentration of such luminous, hot stars known in the entire Galaxy. Within $\sim 1''$ (0.034 pc) of its core, it contains all three of its optically very bright WR stars (all of H-rich WN6 subclass; one is a short-period binary), which spatially mingle with some of its O3 stars. Since there is little doubt of the coeval nature of such a dense configuration, it would thus appear that O3 stars evolve via mass-loss very rapidly into H-rich WR stars, even before they leave the H-burning main-sequence. Why these WR stars are optically so bright, however, remains a mystery: possibly their true bolometric correction is reduced (leading to lower *bolometric* luminosities), as their relatively cool winds are too strong to allow us to see down to their hot photospheres; or (less likely) the 3 WR stars show rotation-enhance luminosities (cf., Fliegner & Langer 1995). This is a new result, which is made clear thanks to the large number of massive stars seen in a very small volume. Note that even the sub-volume of NGC 3603 observed spectroscopically by *HST* (out to $3''$ from the centre) revealed a sufficient number of O and WR stars to ionize the entire surrounding (Giant) nebula to account for the observed H_α and radio continuum fluxes. With the additional luminous stars found subsequently from ground-based work in NGC 3603, but outside this (*HST*) volume, there are more than enough ionizing photons, which then must be leaking out.

5.3. Structure

While the looser starburst regions are not expected to show strong dynamical evolution over a nuclear time interval for massive stars of $\approx$ 10 Myr, the denser ones will. This is nicely illustrated by Elson et al. (1989) who show how core radii of massive clusters evolve with time. Starting with their youngest tabulated cluster (R136), the core radii increase from a fraction of a parsec systematically up to several pc over a Gyr, before core collapse ensues in the most extreme cases. This is modeled by mass-loss from evolving stars (especially rapid at the beginning, when massive stars dominate) with an IMF that is slightly flatter than that of Salpeter (1955), in agreement with our assessment of $\Gamma = -1$ above.

NGC 3603 also has a very small core, if it has one at all (Moffat et al. 1994a). In fact, it resembles R136 in projected star-density and stellar content so closely, that it appears to be a clone. However, the analogy stops there, since R136 is surrounded by an envelope of stars with similar density profile out to a radius of some 10(pc (Moffat et al. 1987), while NGC 3603 completely lacks such a halo outside r = 1 pc. One can only speculate that this difference may be due to greater tidal effects in the Galaxy, especially in the disk.

6. CONCLUSIONS

- Extreme starbursts may appear rare and exotic, but given the selection effects that prevail; there is no compelling reason to suppose that their basic stellar content (other than total number) is any different from star-forming regions of low density or total mass.
- The stellar initial mass function (IMF) appears to be universal and is possibly represented by a unique single power-law downwards from some 100 $M_\odot$.
- The nearby Galactic starburst region NGC 3603 is a nearby clone of the exotic core R136 of 30 Dor in the LMC. But NGC 3603 is some 7 times closer than R136, offering a unique opportunity to study a dense starburst region at relatively close range.

7. FUTURE

Some musings for the future:

- NGC 3603 is only one case in the Galaxy; we need more, truly nearby, dense starbursts. Adequate resolution IR imaging surveys Galaxy-wide are needed to probe for other similar regions. Nevertheless serendipitous IR studies of some optically hidden young regions of star formation may be fruitful, such as the potentially very dense starburst IRS 2 within the molecular cloud W51 (Goldader & Wynn-Williams 1994).

- Individual stellar velocities are needed in the densest regions, in an attempt to probe the mass distribution and hence the IMF at the low-mass end, at least indirectly. However, this is a challenge, since OB-star radial velocities are notoriously imprecise. We are attempting this in NGC 3603 nevertheless (Moffat et al., in preparation). Perhaps appropriate astrometric data will become available to help solve this.

- Direct (Keplerian-orbit binary) masses are still needed for the most massive stars, often found in the most massive starbursts. This would help solve the current discrepancy among evolutionary, spectroscopic, and binary masses, which tend to form a decreasing progression, which becomes enhanced for the most massive stars (although see Lanz et al. 1996). The most massive star so far "weighed in" is the WR component in the Carina Nebula binary HD 92740, with $\geq 72 M_{\odot}$ (Rauw et al. 1996). J.-F. Bertrand et al. (in preparation) are systematically searching for binaries among the most massive stars in 30 Dor.

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