RevMexAA (Serie de Conferencias), **8**, 1–8 (1999)

RESOLVED YOUNG OPEN STAR CLUSTERS: KEYS TO UNDERSTANDING MASSIVE HOT STARS

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RESUMEN

¿Qué se puede aprender de una estrella caliente, de gran masa, que está aislada? ¡Muy poco! No solamente su distancia es incierta, sino que también otros parámetros más fundamentales tales como edad, masa y composición, permanecen relativamente ambiguos. Todo esto cambia, sin embargo, cuando consideramos estrellas de gran masa en grupos jóvenes. Y esto es especialmente cierto en cúmulos densamente poblados donde, a pesar del incremento en la dificultad para hacer fotometría de precisión, la edad y composición inicial tienen menor probabilidad de variar de una estrella a otra, sin mencionar las ventajas de una distancia común, un enrojecimiento uniforme y una muestra estadísticamente más significativa. Las variaciones en el principal parámetro restante, la masa, nos permiten un análisis de la evolución estelar y la función inicial de masa. Por último, el conocimiento adquirido en el estudio de estrellas individuales en cúmulos cercanos resueltos, puede aplicarse a cúmulos lejanos no resueltos. Esto tiene especial relevancia para los estudios de edad y composición, y en consecuencia, formación y dinámica de cúmulos distantes ricamente poblados como componentes básicos, por ejemplo, de protogalaxias próximas al borde del Universo.

ABSTRACT

What can be learned from an isolated, hot massive star? Very little! Not only is its distance uncertain but other more fundamental parameters like age, mass and composition remain relatively ambiguous. This all changes, however, when we look at massive stars in young groups. And it is especially true in tight, populous clusters, where despite the increased difficulty of doing precision photometry, age and initial composition are less likely to vary from star to star, not to mention the advantages of a common distance, uniform reddening and a decent statistical sample. Variations in the one main remaining principal parameter, the mass, allow us to scrutinize stellar evolution and the initial mass function. Ultimately, the knowledge gained from the study of individual stars in nearby, resolved clusters can be applied to distant, unresolved clusters. This is especially relevant to trace ages and composition, and hence formation and dynamics, of distant populous clusters as basic building blocks e.g., in proto-galaxies near the edge of the Universe.

Key words: **STARS: EARLY-TYPE — OPEN CLUSTERS: GENERAL**

1. INTRODUCTION

On behalf of my relatively young (now celebrating 20 years only!) home observatory, l'Observatoire du mont Mégantic, Québec, I wish to extend my sincerest **félicitations** to the La Plata University on its **100th** Anniversary! ... and to NGC 3603 (in many ways the jewel of this meeting, along with 30 Dor), celebrating its 2 197 100th birthday.

My self-determined (impossible?) task at this meeting is to attempt to introduce, stimulate, provoke, entertain..... all about hot stars and their parent clusters. .... ¡pero cuidado! ... my background credentials have developed in a completely backward way compared to "everyone" else today (apparently), i.e., from *large*- to *small*-scale:

- from the extragalactic distance scale (Cepheids in M31) (M.Sc., Univerity of Toronto, Canada, 1966, with S. van den Bergh),
- via Galactic open star clusters and Galactic structure (Dr.rer.nat./Dr.Habil., Ruhr-Universität Bochum, Germany, 1970, 1976, with Th. Schmidt-Kaler),
- to properties of massive stars, in particular Wolf-Rayet and O-type.

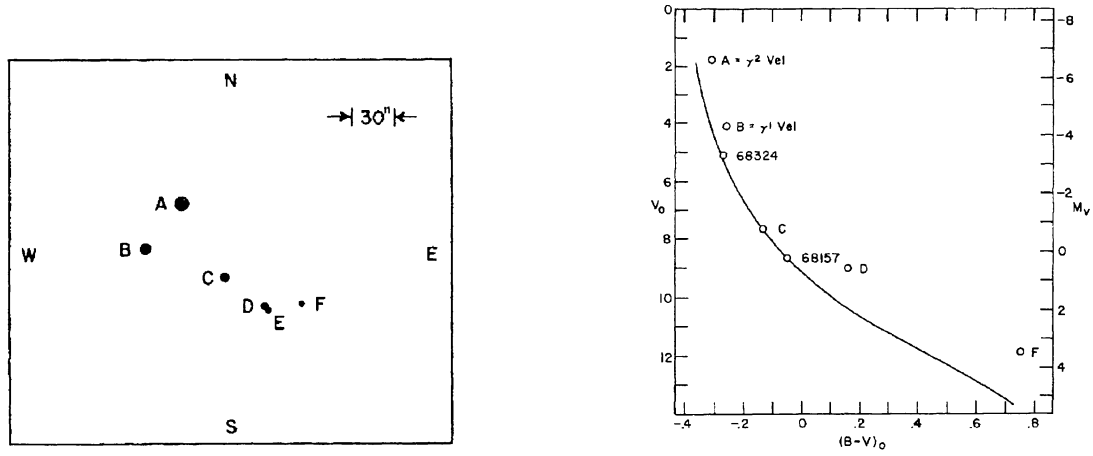

Fig. 1. Identification and color-magnitude diagram of the sparse γ Vel stellar group, (from Abt et al. 1976).

So despite this anomaly, let me try to whet your appetite starting with a little slide show from far to near, starting with the Hubble Deep Field. This now famous field should serve as a reminder that if we are going to understand young, blue galaxies, we need first to understand luminous, hot stars contained in them.....

2. WHAT ONE CAN(NOT) LEARN FROM AN ISOLATED, LUMINOUS, HOT STAR

In order to understand an individual star on its own, one requires a minimum of information. Neglecting kinematics (e.g., radial velocity and proper motion) and parallax (not yet available for most luminous stars) this could be *UBV* photometry or, better, *BV* photometry plus an MK spectral type. Three such pieces of information at least are needed in order to determine the interstellar extinction, along with the intrinsic and apparent brightnesses, from which the distance can be found. For O-stars, the "cosmic" dispersion in intrinsic brightness (σ_{M_V}) is typically ~ 0.7 mag (e.g., Conti et al. 1983), leading to a relative error in the distance $\sigma_d/d = \sigma_{M_V}/5\log e \sim 0.3$, i.e., 30%. Such a large error is fatal for tracing spiral arms at even modest distances in the Galaxy. Improvements can be made by going to the Magellanic Clouds, where the distance, even though larger, is essentially constant (and known to fair precision), or to star clusters where the statistical *and* systematic errors in distance are reduced, normally to a net value of around 10% in the best cases. A quantum leap in improvement must however wait for the next generation of high-precision astrometry (parallaxes) of hot, luminous stars, mainly from space.

Although one can get by with pure photometry (e.g., *UBV*), having a good spectrum increases the value of the photometry enormously (Massey 1985). Not only does the spectrum lead to a reliable estimate of the *intrinsic* colour (or effective temperature) and luminosity of the star, it provides a constraint on the age.

3. CLUSTERS SMALL AND LARGE, SPARSE AND RICH, DUST-FREE AND OBSCURED

Young star clusters that contain luminous hot stars, the subject of this workshop, come in various sizes, density and degree of obscuration. This necessitates different techniques of observation, in order to secure comparable information in each case.

At the small and sparse end of the scale, life is simple, but the information content is also minimal. An example is the γ Vel group within the Gum Nebula (Brandt et al. 1971; Abt et al. 1976) —see Fig. 1. Not only is the distance uncertain, subject to small numbers, but also the gaps between neighbouring stars in the color-magnitude diagram (CMD) are large, making it more difficult to connect stellar evolution at different masses. Nevertheless, one has the considerable gain over a single star, of knowing something about the position of the observed ZAMS, which yields a better distance. At least the main thing going for small and sparse is that *large* and sparse would be worse!

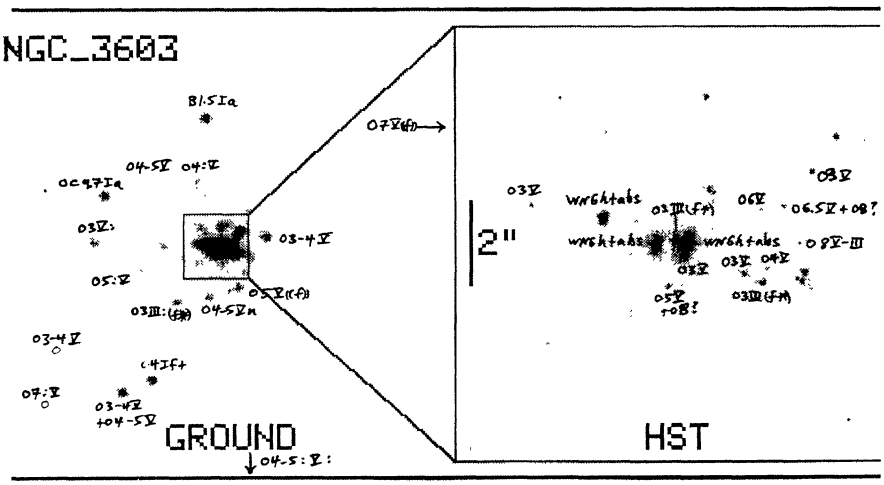

Fig. 2. Groundbased versus *HST* images (even before correcting the optics!) of the Galactic starburst region NGC 3603. Spectral types are indicated, from Drissen et al. (1995) for *HST* and (preliminary) from Moffat et al. (1999) for CTIO/4-m. Note the large number of early O stars.

Still fairly small, but *very dense* young clusters are a different kettle of fish. In particular, the core of 30 Doradus in the LMC, R136, and its much nearer clone, the Galactic cluster NGC 3603, come to mind as being probably the densest, young (c. 2 Myr: de Koter 1998; Crowther & Dessart 1998) clusters known. At the periphery of these dense regions, star formation is still going on, probably being triggered by the ram pressure of the expanding shock-wave bubbles from the combined winds of the large number of hot, luminous central stars (e.g., Walborn & Barbá 1998). Such dense clusters, though, require high spatial resolution even in the Galaxy, as available with the *Hubble Space Telescope* (see Fig. 2). Beyond the LMC, however, even better resolution will be required to fully understand such exciting systems.

Embedded young clusters pose their own unique problems. They can either be a result of extreme youth, where their placental clouds have not yet dissipated, or a result of large distance in the Galactic disk, behind large quantities of interstellar extinction. Examples are, respectively, M17 of age c. 1 Myr (Hanson, Howarth, & Conti 1997) and the Galactic centre cluster, probably having a complex formation history (e.g., Krabbe et al. 1995; Tamblyn et al. 1996).

4. IMPORTANCE OF CLUSTERS

As will be discussed later in more detail at this workshop, the main importance of clusters for hot-star research is threefold: (1) constrain stellar evolution, (2) calibrate specific classes of stars (e.g., in order of increasing age for massive hot stars: ultra-compact H II regions, main-sequence OB stars, OB supergiants, Of stars, OBe stars, Luminous Blue Variables, "slash" stars intermediate between Of and WR, and Wolf-Rayet stars), and (3) determine the initial mass function. The advantage of clusters is clear: only one prime parameter varies from star to star: the (initial) mass. In the best cases, one has constant age and initial abundances, although there still can be a spread in rotation properties and binary frequency. Of course internal dynamics is another important aspect even of young star clusters (e.g., Elson, Freeman, & Lauer 1989), although this was not the main thrust of this workshop.

In order to optimize the utility of clusters in this context, it is clearly advantageous to emphasize compact, rich clusters, where one is least likely to have to deal with other internally varying parameters besides the mass. This also helps avoid statistical gaps in the CMD and a spread in interstellar extinction, as well as in age and metallicity. As far as age spread is concerned, Elmegreen (1997a) has nicely summarized recently how the age spread of star-forming regions depends on the size (see Fig. 3). The timescale of star formation goes as $t_{\rm SF} \sim D/c$, where D is the size and c is the turbulent speed of the ISM, which has been found empirically to obey the famous relation: $c \sim [D({\rm pc})]^{1/2}$ km s^{-1}. Thus, $t_{\rm SF} \sim [D({\rm pc})]^{1/2}$ Myr. This is borne out fairly well in regions like the Carina OB1 complex (e.g., Turner et al. 1980; Feinstein 1995).

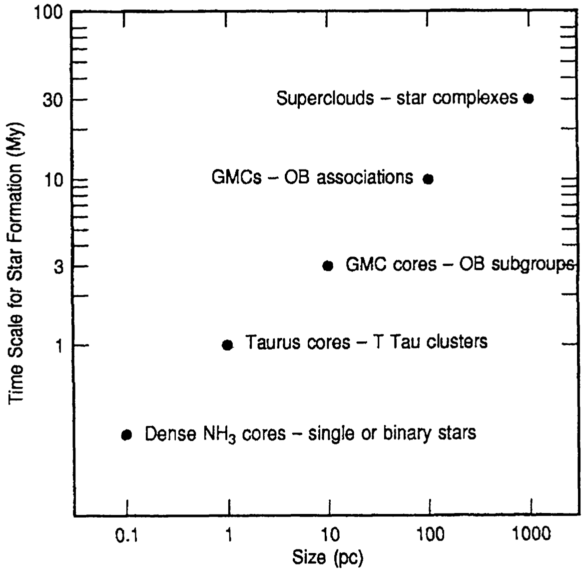

Fig. 3. Star formation timescale for regions of various size (from Elmegreen 1997a).

Do all (massive) stars form in clusters? This question has been debated for many years. I am convinced that they are, with some influence from the three following (somewhat condensed) quotes, which leave one to ponder:

- Iben & Tutukov 1997: "... 25% of gas/dust is converted into stars during typical SF episodes in clouds. When massive stars form, they heat the remaining gas to $\sim 10^4$ K and drive this gas/dust *out* of the cluster. This leads to a reduction of the cluster total mass and escaping of stars. Thus, somewhat less than 95% of these clusters die at the moment of birth!" [Hence, most (all?) field stars must have been ejected at some time.]

  "The open clusters we do see (e.g., Pleiades, Hyades) are very rare, long-term survivors. But even they are in the process of evaporating. Such clusters survived because the process of SF was more efficient in them."

- Kaper et al. 1997: "... Given the large number of O-type runaways, it might well be that all O-type stars were born in associations, and that the whole field population consists of runaways."

- Lada, Evans, & Falgarone 1997: "... Numerous near-IR imaging surveys of molecular clouds lead to the conclusion that extremely young, embedded clusters are considerably more numerous than previously suspected. In fact, they may be so numerous, that they account for the formation of the majority of stars, independent of stellar mass, being formed in the present epoch of Galactic history."

5. THE STELLAR IMF AND ITS RELATION TO TURBULENT FRACTAL CLOUDS

5.1. Observations

One of the most exciting recent developments in cluster work concerns the initial mass function (IMF). The IMF is very fundamental, reflecting how stars form from their placental nebulae. Its determination is best done in rich, compact clusters, where one has a good statistical sample of stars of different mass all formed at nearly the same time. A clear understanding of *unresolved* clusters, starbursts and even whole galaxies depends not only on stellar evolution, but also on the relative importance of stars of different mass at the outset, i.e., the IMF.

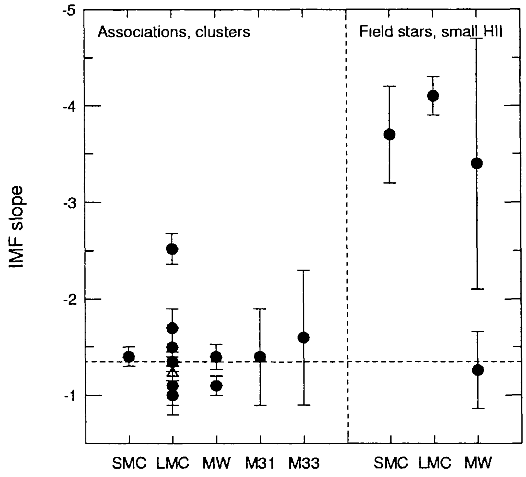

Fig. 4. Initial mass-function slope for different environments (from Hunter et al. 1997).

In the past 5 years or so, it has become more and more evident that the IMF is essentially "Salpeter" everywhere, at least for massive stars, regardless of ambient metallicity, stellar density, cluster size, or almost any other imaginable parameter (e.g., Moffat 1997; Hunter et al. 1997 —see Fig. 4). In the usual form, $N(m)dm \sim m^{-\gamma}dm$, with $\gamma \equiv 1 + \Gamma$, where Γ refers to logarithmic binning = 1.35 for the Salpeter (1955) case. This value applies, within the errors, in all clusters studied appropriately, with masses ranging from $\approx 1 - 100\ M_\odot$, and possibly even extending to and below Brown Dwarfs. Most remarkable is the 30 Dor core, R136, which is close to Salpeter over this entire range, $\sim 1 - 100\ M_\odot$. The few exceptions claimed in clusters, often have also fallen in line with the Salpeter value when restudied by others.

However, in the field outside clusters, Massey et al. (1995) have found evidence for a significantly larger value of $\Gamma \simeq 4$ in the Galactic and Magellanic Cloud fields. Even though this has been disputed for the LMC field based on UV imaging by Parker et al. (1998), who find a slope that is more in line with the Salpeter value, there is no lack of theoretical explanations for a different value. For example, Elmegreen (1997b) suggests that for low SF efficiency rates, as in the solar neighbourhood, most clusters in molecular clouds end up *unbound*, with lower mass stars ejected more often than higher mass stars (cf. also Leonard & Duncan 1990). On the other hand, maybe Massey's results are spurious. Indeed, Salpeter's (1955) original result was based on Galactic field stars in the Solar neighbourhood, although only in the range $0.4 - 10\ M_\odot$, compared to $M > 25\ M_\odot$ for Massey's stars.

5.2. Observation of Structure in the ISM

During the past 10 years or so, evidence has been mounting that the ISM (e.g., H I, H II, dust, molecular clouds = MC) is highly structured and best described by a hierarchy of fractals (e.g., Scalo 1990). In fact, a power law describing the structures, of the same form as the IMF for stars, $N(m)dm \sim m^{-\alpha}dm$, with $\alpha \simeq 1.7$ fits many data sets best, over a total of some 10 orders of magnitude in mass (e.g., in MCs: Stutzki 1993). The remarkable similarity between the ISM structure and the IMF of stars that form in these MCs begs an explanation.

5.3. Theory and Connection Between the IMF and ISM Structure

According to Elmegreen (1997b), the dense parts of self-gravitating MCs represent the cradles of SF. Thus, the IMF is the ultimate result of the hierarchical, fractal structure of the ISM. This leads to the formation of multiple groups and clusters of stars, instead of isolated stars. Elmegreen's (1997b) model of random mass sampling in a fractalized cloud leads naturally to a power-law distribution, with $\alpha = 2$ and $\gamma = 2$. However, observations yield (1) typical values of $\alpha(obs) \simeq 1.7$, not 2.0, due to a bias against the observation and identification of (especially small) cloudlets, and (2) typical values of $\gamma(obs) = 2.3$, not 2.0, due to two factors: a competition for mass and a density dependence for the SF rate (Elmegreen 1997b).

In this context, it is interesting to note that *clusters as a whole* obey a similar power law $N(m)dm \sim m^{-2}dm$ (e.g., Ho 1997), for the same reason (hierarchical fractal formation on large scales, as on small scales). This implies that a very significant fraction of SF occurs in *small* clusters.

The invariability of the IMF and the ISM structure power-law slope as well as their mutual similarity (even identity, given the biases) may not be all that surprising, if one accepts that both are related and a consequence of turbulence in the ISM. In fact, as R.N. Henriksen has often suggested to me (cf. Moffat 1997): "It doesn't matter what the detailed physics is, the resulting power law is always $\sim$ the same when dealing with supersonic, compressible turbulence." This may be a curse and a blessing at the same time, depending on your point of view! Also relevant in this context is an important statement by Elmegreen (1997b): "SF does not proceed from large to small scales in a cascade of collapse, as was once thought. Rather, SF occurs $\sim$ simultaneously on all scales, with smaller regions coming and going many times before the larger regions are finished." This would imply that cluster ages based on high mass stars should be the same as estimates based on the low-mass stars in the same cluster. Current observational results on this are conflicting at present, in await of the final jury...

So much for the slope of the IMF. What can one say about the upper (and lower) mass limit, m_u (m_l) of SF? While one might expect m_u to vary with metallicity, as the Eddington limit for stability is Z-dependent, observations of luminous stars in galaxies would suggest otherwise (e.g., Humphreys 1986). Furthermore, the claimed fluctuations in m_u from cluster to cluster might very well be dominated by statistical effects, depending on the total sample (Elmegreen 1997b; Massey 1998a) and have nothing to do with a true variation in m_u. Taking $\int_{m_u}^{\infty} N(m)\, dm \equiv 1$ (valid for $\gamma > 1$, otherwise the integral diverges), and $\int_{m_l}^{\infty} N(m)\, m\, dm = m_{\rm total}$ (valid for $\gamma > 2$, otherwise the integral diverges), one finds for the above power-law IMF:

$$m_u = k(m_{\rm total})^{1/(\gamma-1)},$$

where the constant $k = G^{1/(\gamma-1)} m_l^G$, in which $G = (\gamma-2)/(\gamma-1)$: This means that for $\gamma = 2.35$, m_u increases as $0.20\ M_\odot\ m_{\rm total}^{0.74}$, for $m_l = 0.1\ M_\odot$. Such a relation is suggested in observations of young open clusters (Elmegreen 1997b). However, for very large masses ($m_{\rm total} > 10^5\ M_\odot$), m_u exceeds 1000 $M_\odot$, which does seem excessive. This could be alleviated for lower values of $m_l << 0.1\ M_\odot$, which might be reasonable. On the other hand, if one were to take all the young clusters together in the Galaxy, the resulting statistical m_u calculated this way would become absurdly large. Furthermore, if the true value of γ turns out to be closer to (or even less than!) 2, there would have to be a finite upper-mass cut-off, as expected from Eddington limit arguments for massive stars. I conclude that, although statistics may influence the value of m_u, ultimately a real value must also exist in nature, probably somewhere close to $\sim 10^2\ M_\odot$. This remains to be proven, however. A corollary to this consideration of progressively poorer statistics as one goes up the H-R diagram, is that reliable ages are very difficult to determine in the case of sparse, young clusters.

For the sake of completeness, even though it is not part of this meeting, on the other end of the scale one might expect m_l to correspond to the thermal Jeans' mass in the SF cloud, close to 0.3 $M_\odot$, but dependent on metallicity. However, this is certainly not true, since we do see brown dwarfs! In fact, if the same IMF slope as is valid for medium/high-mass stars continues down through and below 0.1 $M_\odot$, one can calculate the ratio R of non-luminous stars to luminous stars, $R \equiv [\int_{m_l}^{0.1} N(m)\, m\, dm]/[\int_{0.1}^{100} N(m)\, m\, dm] = [(0.1/m_l)^{\gamma-2} - 1]/[1 - 10^{-3(\gamma-2)}]$. For finite m_l below 0.1 $M_\odot$, R is negligible for $\gamma < 2$; "a few" for $\gamma = 2$; and much greater than unity for $\gamma > 2$. At the present rate at which brown dwarfs are being discovered, the value remains open. This exercise, together with the above consideration dealing with the upper mass-limit, illustrates the importance and critical nature of the IMF slope.

6. (UNANSWERED) QUESTIONS...

I will terminate by giving a list of mainly unanswered questions for massive, hot stars. Young open clusters would definitely help answer many of these. This is a personal list, not intended to be exhaustive; rather the purpose is to provoke further consideration at this meeting.

- How reliable are theoretical models of (the most) massive stars? Of crucial importance are the mass-loss rates, which may not be as well known as one would like to think (e.g., de Koter 1998)!

- A possibly related current question concerns the mass discrepancy (evolution versus spectral line analyses versus Keplerian masses; e.g., Lanz et al. 1996). Ultimately, I feel that this will be solved only by the last of these, which is the least model-dependent, although one has to allow for possible binary interaction effects.

- What is the upper initial mass limit that leads to the formation of a red supergiant? Current theory would indicate somewhere close to 40 $M_{\odot}$ (Maeder & Conti 1994). However, RSG and WR stars are mutually exclusive in Galactic open clusters; hence if stars of c. 25 $M_{\odot}$ and greater pass through the WR stage for Solar metallicity as predicted and observed, then the RSG upper limit must be below $\sim$ 20 $M_{\odot}$. A striking manifestation of this is the famous cluster pair h and χ Persei (a beautiful colour image appears in Sky & Telescope for 1998 Feb., on page 74): neither cluster has WR stars, yet while the slightly younger h Per has no RSG, χ Per does have a significant population of RSG. Another manifestation is Massey's (1998b) finding of an upper-mass limit of RSG in the range 13–18 $M_{\odot}$ in the whole of M31 and M33.

- What are the real positions of WR cores in the H-R diagram? Most modeling is done including an optically thick wind, whose parameters are not well known. Ultimately, as for other stars, one will always want to know where to place the hydrostatic core, where the star ends and the wind begins.

- Can very massive ($m_i > c.100$ $M_{\odot}$) stars on or very near the main sequence show WR features? Observations and isochrone fitting of very young, massive clusters, like R136 and NGC 3603 would indicate this is likely to be the case (e.g., de Koter 1998; Drissen et al. 1995).

- What is the true evolutionary scenario from birth to death of massive stars? A global pattern of O through Of or BSG and LBV, then WR to a supernova is generally agreed upon by most experts in the field, although details are controversial.

- Do all stars form more or less simultaneously, independent of their initial mass?

- Is the IMF shape *really* constant, independent of metallicity, density, size, etc. of the forming region? Recent mounting evidence might suggest that it is, with important implications for connections to turbulence in the natal clouds. However, outside the range [0.1, 2] $Z_{\odot}$, we know little about this.

- Do all (massive) stars form in clusters/associations/groups?

- Is the upper limit of star formation, reflected by the Humphreys/Davidson limit (e.g., Humphreys & Davidson 1994), really the same for different galaxies? Present observations would suggest this to be the case, as surprising as it seems (since metallicity-related opacity effects are expected to lead to higher masses in lower metallicity environments) although statistical noise prevents making a definitive statement.

- Why are there no young, populous (Globular-like) clusters in the Galaxy, as in the LMC, SMC? NGC 3603 (= clone of the core of 30 Dor, R136) may be the rapidly evaporating remains of such a cluster in the Galaxy.

I am grateful for financial aid from NSERC (Canada) and FCAR (Québec).

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