THE STELLAR CONTENT OF SPIRAL ARMS

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ABSTRACT. I will discuss the spiral arms of our Galaxy as indicated by the Wolf-Rayet star population and their connection to GMCs, the sizes and shapes of some nearby associations in the northern Milky Way, and the slope of the IMF for Cyg OB2 and several regions of the Magellanic Clouds.

1. Introduction

Our knowledge concerning the **stellar** content of spiral arms in our Galaxy is limited to O stars, supergiants, and those highly evolved objects of Wolf-Rayet (W-R) type. These stars should in principle define the spiral structure. By contrast, when we visually examine other galaxies the morphology we observe is usually **not** that of the individual hottest stars but rather the ionized gas (HII regions) excited by these objects along with the older supergiants (which have smaller bolometric corrections and thus are visually brighter). In this review I wish to touch briefly on several aspects of the title, posed as three questions: (1) Where **are** the spiral arms of our Milky Way? (2) What are the **sizes** and **extent of** stellar associations? (3) How **many** massive stars are found in associations **(IMF slope; upper, lower mass "cutoffs")**? This discussion should be considered as a progress report.

2. Where are the Spiral Arms of the Galaxy?

The first identification of the spiral arms of our galaxy, as outlined by stars, was given nearly forty years ago by Morgan et al. (1953) who utilized two dozen northern OB stars with distances up to a few kpc. Humphreys (1970) presented a similar diagram for many supergiants (in both hemispheres) and the positions of multitudes of O stars and W-R stars have been considered by Garmany et al. (1982), and van der Hucht et al. (1988), respectively. Interspersed with these efforts have been radio observations of the cool HI gas and hot HII regions (a thorough discussion was given by Georgelin and Georgelin (1976). The cold gas and H_2 can be traced out by CO measurements at 2.6mm; a summary is provided by Combes (1991). Galactic structure determinations based upon stars has the advantage that the distances can be determined from well established calibrations of the spectral subtypes. Unfortunately, stars are difficult to observe at great distances, or through appreciable Galactic extinction and

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stellar surveys are very incomplete. By contrast, HI and HII regions and CO clouds can be observed across the galaxy and the surveys are reasonably complete. They suffer from less certain distance estimates, being derived from a galactic rotation model with kinematic uncertainties (non-circular velocities).

I would like here to discuss a connection between the distribution of W-R stars and massive molecular clouds (GMCs) in the Galactic plane. W-R objects are the descendants of the most massive O stars (Conti et al. 1983; Humphreys et al. 1985) and should be excellent indicators of extreme Population I. These stars have very strong winds leading to a broad emission line spectrum (Abbott and Conti 1987). While we do not fully understand the physics of radiative transfer in dense moving media, the strong emission features can readily be recognized on objective prism plates, or with narrow filter techniques (Amrandroff and Massey 1985), and relatively faint objects identified and classified. Using "classic" spectroscopic techniques (calibration of Mv and $(b-v)_0$ with spectral subtypes), Conti and Vacca (1990) have determined distances (good to 50%) to most of the 160 (known) W-R stars of our Galaxy. For W-R stars within 4 kpc, with the most accurate distances, the "z" scale height is 45 pc, thus they are indeed extreme Population I. The numbers of known W-R stars in our Galaxy are, however, **seriously incomplete.**

Leo Bronfman first called my attention to the spatial correlation between the Galactic GMCs and W-R stars in the fourth quadrant. One would expect that the former objects are the birthplaces of many (all?) associations and massive stars. The latter, with (total) ages of only a few million years, cannot move far from their origins. I would like to present a **preliminary** plot here; a more complete discussion will be presented elsewhere (Conti et al. 1992). In Fig. 1 I show the distribution of massive GMCs inward from the sun (longitude only from 280 to 45 degrees - obtained from Bronfman) overlain on the W-R stars (from Conti and Vacca 1990). There is in the fourth quadrant a nice correlation between some of the GMCs and several W-R stars, especially at large distances of 10-12 kpc towards longitudes 315 and 340 degrees (which might be identified with the "Scutum-Crux" and "Norma arm" features, respectively, of Georgelin and Georgelin 1976). There appears to be a long trailing arm (Sag-Carina) near the sun towards 290 degrees (Shara et al. 1991 have detected a well-defined additional 13 W-R stars in just this direction, four at large distances).

There is a curious absence of **either** GMCs or W-R stars from 4-9 kpc away from the galactic center between 310 and 340 degrees; neither spiral arm as defined by these objects extends through this region. Furthermore, closer to the sun in these same directions and around through the galactic center to about 20 degrees longitude, there are considerable numbers of W-R stars and GMCs, with **no discernable delination of "arms"**. One has the impression that these relatively nearby extreme Pop I indicators have the distributon of a **bar** inward from the sun, aligned along an angle behind it. One is reminded of the arguments given by Blitz and Spergel (1991) that our Galaxy is a tri-axial ellipsoid with major axis aligned at 45 degrees with respect to the sun line to the Galactic center. Their Fig. 10 schematic representation is in reasonable agreement with the distribution shown in Fig. 1 (the more distant W-R stars towards the first quadrant are, of course, missing - hidden behind the extensive dust in these directions). More complete statistics on W-R stars would greatly help our understanding of Galactic structure.

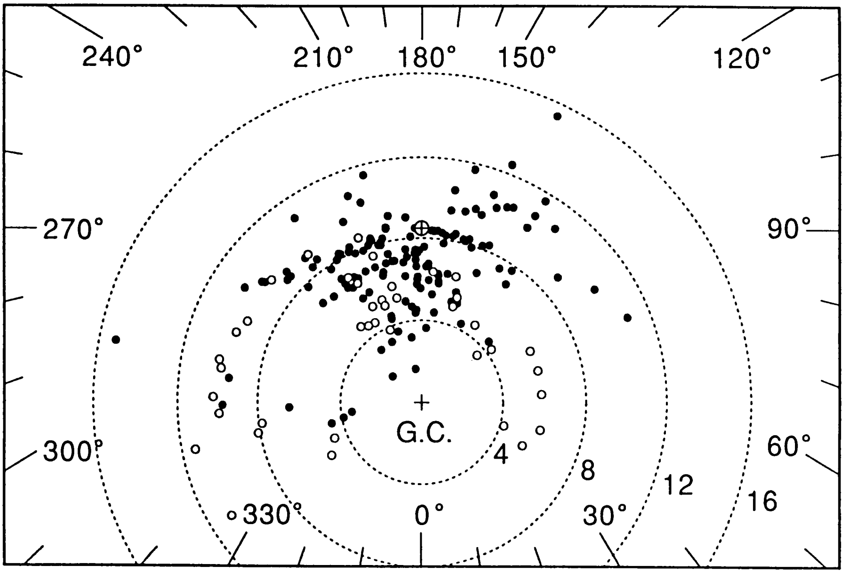

Figure 1. Galactic plane distribution of W-R stars (Conti and Vacca 1990). Filled circles, and GMCs (Bronfman, private communication). Open circles, with $M > 10^6\ M_{\odot}$. Is a "bar" inward from the sun present in these data?

3. What are the Sizes and Extent of Galactic Associations?

I would like to share with you some of the work my colleague Dr. Garmany and her associates are doing to answer these questions. Stellar associations are groupings of very young stars at comparable distances with similar kinematic properties. Proper motion information for O stars with distances of kpc is difficult to obtain; radial velocity data is often compromised by binary stars. A necessary requirement is that all stars belonging to an association be at the same distance. This step requires careful spectral classification and reliable photometry, especially for the Galaxy, to accurately derive the extinction and the distance for individual stars.

Garmany and Stencel (1991) have re-discussed the membership of a number of nearby associations in the northern sky using data in the literature and newly acquired spectra and photometry. Figure 2 displays a small region of their survey. The upper panel shows the IAU defined association boundaries (aligned with the cardinal directions!); the lower panel is a hand drawn attempt to encircle only those OB stars and supergiants that are at similar distances.

The relatively distant Cep OB3 association is about half the IAU size; the nearby Cep OB2 star group has a distinctly non-rectangular shape; Cep OB1 appears to be two subgroups. The physical sizes are about 50 - 100 pc when one takes account of the distances. Careful analysis like this must proceed over the entire Galactic plane before we can be completely confident of the stellar populations in various associations. In the Magellanic Clouds, association perimeters are more readily determined from just photometry since the distance ambiguity does not exist (e.g. Lucke 1972).

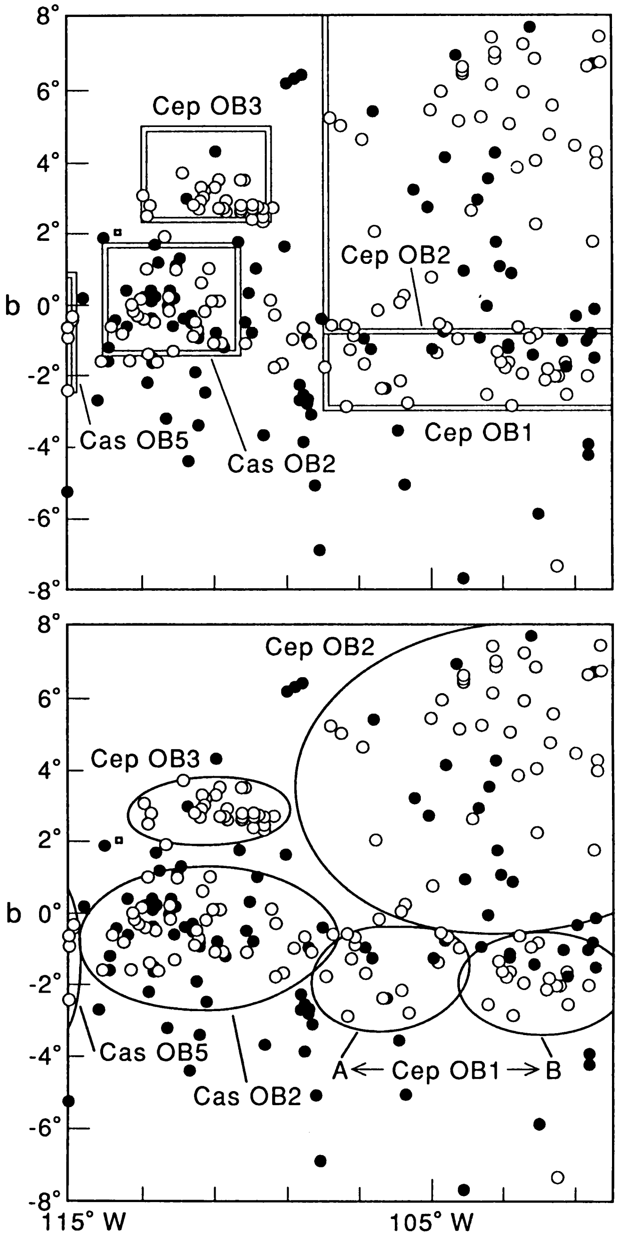

Figure 2. Spatial distribution of early type stars and supergiants. The open circles are stars at the same distances, thus defining the listed association; the filled circles are other stars. Upper panel: IAU defined boundaries; lower panel: hand drawn circumferences of associations (adapted from Garmany, private communication).

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4. How Many Massive Stars are Found in Associations; IMF; Upper, Lower Mass Cutoffs?

Following Scalo (1986) one can define the slope of the Initial Mass Function as $\Gamma = d \log \xi(\log m)/d\log m$ where $\xi(\log m)$ is the mass function in units of number of stars born per unit logarithmic (base ten) mass interval per unit area. For a power law mass spectrum $f(m) = A\, m^{\gamma}$ and the index $\gamma = \Gamma - 1$. In Tinsley's (1980) notation, $\gamma = -(x+1)$ and $x = -\Gamma$; in these units the Salpeter (1955) slope is $=-1.35$. Garmany et al. (1982) utilized published photometry, spectral types and luminosity classes to place the OB stars within 2.5 kpc of the sun on a theoretical HR diagram constructed with mass tracks. It was then a simple procedure to count all the stars within various mass ranges and determine the IMF slope. Their result suggested that for massive stars $\Gamma = -1.3$ inward and $= -2.1$ outward of the solar circle. The statistics of this 5 kpc diameter region may not be complete (e.g. Humphreys and McElroy 1984) and a distinction between the inner and outer galaxy might not exist. Additional identifications of OB stars within this volume are currently underway by Garmany and associates and future results will be forthcoming.

I will now consider recent work on the massive star content of several well studied associations in the Magellanic Clouds, along with Cyg OB2, by Garmany and Massey and colleagues. Their procedure is to first acquire CCD UBV photometry to derive the reddening and Mv accurately. They then take spectra of the bluest and brightest stars so as to obtain accurate effective temperatures of the O stars (for which the photometry is degenerate - Massey 1985). For B0.5 and later type stars, the B-V colors are sufficient to determine temperatures. The stars are then located on Maeder and Meynet's (1988) evolution tracks and enumerated with respect to the masses. This leads directly to Γ with an estimated uncertainty of perhaps 0.2 in the slope.

Massey et al. (1989a) have studied LH 117 and 118 in the LMC. An analysis of NGC 346, the brightest HII region in the SMC, was made by Massey et al. (1989b). In that paper, they give a nice demonstration of how one would derive a different (steeper) slope for the IMF if one used **only** photometry for the O type stars. Parker et al. (1991) have analyzed two other associations in the LMC, LH 9 and LH 10. The latter is the next brightest HII region after 30 Dor. Massey and Thompson (1991) have discussed Cyg OB2. At the poster session of this meeting, Parker has given preliminary results for the 30 Dor region. Parker and Walborn (1991) have recently suggested that Γ varies within the 30 Dor complex and it may depend on sequential effects of star formation. All of the studies listed here have treated the comparable data in the same fashion; thus differences in Γ are undoubtedly significant.

Table 1. IMF slopes for various associations.

Association	Γ	galaxy
Galaxy field (inner)	-1.3	Milky Way
Galaxy field (outer)	-2.1	Milky Way
Cyg OB2	-1.0	Milky Way
LH9	-1.6	LMC
LH10	-1.0	LMC
LH117	-1.8	LMC
LH118	-1.8	LMC
30 Dor (mean)	-1.5	LMC
NGC 346	-1.8	SMC

There are substantial differences in the derived values of Γ for Cyg OB2, LH10 and portions of 30 Dor (Parker and Walborn 1991) compared to the other associations, which are similar to one another. Furthermore, the Γ are **not** a simple function of the metal abundances (which are lower in the LMC and SMC than in the solar vicinity). These conclusions are the results of careful investigations based upon **direct counts of stars** and would seem to be firmly established.

A perusal of the referenced papers reveals **no** evidence for **upper mass cutoffs** of star formation, beyond the statistics of each association. There is also **no** evidence from star counts bearing upon the existence of **low mass cutoffs**. One could imagine a scenario in which the formation of large numbers of massive stars, with their attendant radiation and winds, might snuff out formation of low mass stars. 30 Dor is a likely location and deep photometry of this region might reveal such a phenomenon if it exists.

Studies of the integrated properties of other galaxies have sometimes suggested the existence of upper or lower mass cut-offs. For example, Reike et al. (1980) suggest a general absence of low mass stars in the starburst region of M82; this result has been critcized by Lester et al. (1990). My reading of the controversy is that the jury is still out, but my instinct is that low mass cut-offs may occur under extreme conditions; the study of 30 Dor will tell the tale. As another example, Joseph (1991) suggests that the HeI 2.058 μm/Brackett γ line ratio observed in the starburst galaxy NGC 3256 implies no O stars earlier than type O8. While the argument seems sound, it appears to me that this may merely be an effect of evolution. While the age of the burst may well be 12 million years, as suggested by Joseph, it could well have more recently **turned off**. Then the absence of hotter O stars would merely be an effect of subsequent evolution away from the main sequence. This may also be the situation in NGC 1569 (Waller 1991), a starburst galaxy with bright blue stars (B supergiants?) and strong diffuse Hα but without evidence for high excitation from early O stars. The peculiar gas morphology might be due to numerous recent SN events, something that might be expected if the burst is over and the late type O stars are just now dying.

5. Some Future Perspectives

Population studies of relatively nearby giant HII regions such as 30 Dor can lead us to a better understanding of more distant starburst galaxies. When we investigate more distant objects, individual stars cannot be identified and we must depend on integrated spectra. It is thus important to couple our nearby stellar census with **spatially integrated** spectra of the same regions. In this connection, we (PSC, Mark Phillips and Bill Vacca) have obtained an 8'x8' minute moderate resolution spectrum of the 30 Dor region (by drifting slowly in RA and accumulating counts on the CCD). Estimating the number of Lyman continuum photons (NLyc) from the Hβ flux in the usual way, and taking one O7V star to provide 7 x 10^{48} Lyc/s, we predict the presence of about 100 O7V "equivalents." We believe this is reasonably close to the number of hot stars present but will have a better result when Parker's PhD census of 30 Dor is complete. (We also plan to obtain higher resolution spectra and do a "full blown" analysis of the entire emission line spectum).

Finally, let me turn to a new direction my work has been taking, that of W-R galaxies. These are a subset of starburst galaxies in which a broad 4686 HeII line, due to W-R stars, has been found in the integrated spectrum (Conti 1991). These galaxies also have a strong nebular emission line spectrum, due to the presence of many O stars. In Table 2 I abstract some of the hot star properties inferred for several of these objects, compared to better known nearby HII and GHII regions. The data in the last 3 rows is shown in the poster session here and will be presented in detail elsewhere as part of Bill's PhD thesis.

Table 2. Hot Star Properties of Recent Starbursts

Name	# O7V equivalents	Object
Orion	1 (!)	HII
NGC 346	5	HII SMC
30 Dor	100	GHII LMC
Mrk 1236	1600	W-R galaxy
IIZw40	10000	W-R galaxy
POX 4	30000	W-R galaxy

In the W-R galaxies, the presence of substantial numbers of W-R stars ensures that we are viewing a relatively recent burst of massive star formation. The IMF of these regions may be "flatter" than normal, but other complications (e.g. leakage of Lyman α from the galaxy) may play a role (Vacca and Conti 1992). NGC 346 and 30 Dor are nearby paridigms of the more distant galaxies with many O type and W-R stars and the detailed analyses of their integrated properties, compared to the individual stellar content, will help our understanding of recent starbursts.

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DISCUSSION

Question (V.H. Hughes) We have identified from the IRAS Point Source Catalogue about 220 HII regions (confidence level of 80%) by making use of the color-color diagrams. The HII regions are confined closely to the galactic plane (within 3°). Using radio observations, the HII regions are generally not resolved at 0.3" (maximum sizes of 0.1 pc) and they appear to contain hot stars of similar spectral type. The stellar distribution may be different from what is found in optically observed systems (Hughes and Macleod AJ, 97, 786, 1989).
Response (P.S.Conti) You seem to be suggesting that obscured HII regions might be smaller than optical ones and their stellar content might be different. While I can accept the former, due to their youth, the latter conclusions seems to me to be unlikely. Many HII and GHII regions in the Milky Way are highly obscured and their stellar content not yet studied due to dust extinction. Infra-red spectroscopy might help.
Question (C. Wilson) Two comments: First, I have recently re-identified the OB associations in the inner disk of M33 and MGC 6822 and the mean diameters are roughly 80 pc, very similar to the sizes from Garmany's new boundaries for Galactic associations. Second, the spatial distribution of Galactic W-R stars and molecular clouds more massive than 10^6 M looks very nice, but in the inner kpc of M33, which has recently been surveyed for GMCs, there is not more than one massive cloud, whereas there are 10-20 W-R stars identified.
Response (P.S.Conti) Thank you for reminding me to say that any correlation between W-R stars and GMCs cannot be exact because (1) many W-R stars are completely hidden behind dust in our galaxy, (2) some GMCs might not yet have formed massive stars, or their ages are still less than the formation time for W-R stars (a few million years) and (3) some GMCs may have

been entirely dissipated by the actions of their constituent stellar winds and radiation. Finally, some massive stars, including those of W-R type, do not seem to be associated with any other massive stars, or the spiral structure.

Question (H. Zinnecker) I would like to caution against the IMF slopes you have given for the LMC/SMC associations, mainly because the multiplicity of the massive stars is not resolved. If you placed the Trapezium cluster at the distance of the LMC, the separation of the four stars would be of the order of 0.1 arc second and unresolved in ground based CCD images.

Response (P.S.Conti) I agree binaries are a problem for the absolute numbers. However, I consider it unlikely that the binary fractions in the associations I discussed conspired to be different in just the right way so as to create IMF slope differences when in fact none existed. I need to remind you that this was a differential comparison.

Question (G. Meurer) You say there are about 100 O7V star equivalents in 30 Dor from the integrated spectrum. Do the number counts agree with this?

Response (P.S.Conti) I think they are in rough agreement but this awaits the census currently being carried out by Joel Parker for his PhD thesis.