A Massive Star Odyssey, from Main Sequence to Supernova
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The stellar content of obscured Galactic giant H II regions

Robert D. Blum

Cerro Tololo Inter-American Observatory,
Casilla 603, La Serena, Chile

Abstract. Current research using near-infrared techniques for investigating stellar populations in massive Galactic star clusters is reviewed. In particular, I discuss in some detail a survey of obscured Galactic Giant H II (GH II) regions and the associated stellar clusters embedded in them. The regions have been selected as the most luminous radio continuum sources. This selection criteria has the consequence that the observed clusters are among the youngest massive star clusters in the Galaxy. The emergent stellar populations are further studied through near-infrared spectroscopy of the brighter members, a number of which are young stellar objects with signatures of dense circumstellar material which might arise from in or out-flows, or in disks. New results from 8m class telescopes employing velocity resolved near-infrared spectroscopy and high angular resolution mid-infrared imaging hold great promise for future detailed investigations.

1. Introduction

Near-infrared (1 - 2.5 μm) spectroscopic classification techniques have recently been developed for OB stars (Hanson, Conti & Rieke 1996; Blum *et al.* 1997; Hanson, Rieke & Luhman 1998) and Wolf-Rayet stars (*e.g.*, Eenens, Williams & Wade 1991; Figer, McLean & Najarro 1997). Coupled with infrared spectrometers on large telescopes, these classification schemes are now pushing forward the exploration of optically obscured, young stellar populations throughout the inner Galaxy. As summarized below, near-infrared studies are producing a wealth of new information on the embedded stellar content in GH II regions including the discovery of young stellar objects (YSO), massive star formation processes, and new distance determinations through spectroscopic parallaxes. For the purposes of this review, I take the term YSO to include hydrogen burning objects buried in ultra-compact H II (UCH II) regions.

While this work has concentrated on GH II regions, great progress is also being made on investigating the central stars of compact and UCH II regions (Watson & Hanson 1997; Henning *et al.* 2001; Kaper *et al.* 2002; Hanson 2002) using similar techniques. As shown in the next sections, the GH II region sample is aimed at investigating star formation in the most massive clusters where the presence of multiple O-type stars may affect both the process and resultant mass function. The nearby Orion star forming region is then seen as a transition object between regions of lower mass star formation and higher mass star formation. We can expect the great body of work established in Orion (*e.g.*, Zinnecker

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et al. 1993; McCaughrean & Stauffer 1994; Hillenbrand 1997; Hillenbrand & Carpenter 2000) on the mass function there to provide an important reference point to the GH II region investigations.

The young stellar content in the Galactic center (GC) has also been intensely studied at near-infrared wavelengths. It has been revealed that the stellar cluster in the central parsec, as well as two other nearby clusters, are rich in OB and Wolf-Rayet stars (for recent reviews see Genzel, Hollenbach & Townes 1994; Morris & Serabyn 1996). Figer (these Proceedings) reviews the young stellar content in the GC in detail.

2. Current and recent research

Modern research into the massive stellar content of obscured star clusters began with the GC central cluster in the 1990's with the advent of array imagers and spectrometers capable at near-infrared wavelengths. But it wasn't until the work of Hanson & Conti that the same techniques began bearing fruit in 'normal' Galactic clusters. Hanson, Conti & Rieke (1996) established a catalog of K-band spectroscopic standards which could be (still the definitive classification scheme in the near-infrared) used to obtain spectral types of O- and B-type stars in completely obscured regions. Hanson, Howarth & Conti (1997) then employed these standards in a detailed investigation of the ionizing O- and B-type stars in M 17.

As near-infrared instruments have proliferated, the number of investigations in Galactic star forming regions have grown. Several recent investigations are of interest: work on W 51 (Okumura *et al.* 2000, 2001; Hodapp & Davis 2002), Cyg OB2 (Knödlseder 2000), low mass stars in the star burst clusters NGC 3603 (in the Galaxy, Brandl *et al.* 1999) and R 136 (in the LMC, Zinnecker *et al.* 1999). Dutra & Bica (2001) have used the 2MASS catalog to search for new clusters near the Galactic Center. Fuchs *et al.* (1999) identified luminous near-infrared sources possibly associated with a soft γ-ray repeater. Subsequently, Eikenberry *et al.* (priv. comm.) have obtained spectra of these sources showing them to be super massive stars; the most massive, an LBV candidate may have a bolometric luminosity in excess of $6\times10^6\,L_\odot$.

Blum, Conti and Damineli have begun a survey of Galactic giant H II (GH II) regions (Blum, Damineli & Conti 1999, 2001; Blum, Conti & Damineli 2000; Figuerêdo *et al.* 2002; Conti & Blum 2002a,b; Leandro *et al.* 2003). This survey is on going, and I discuss in some detail below recent results resulting from it.

3. Giant H II region survey

Our sample of GH II regions includes all objects in the list of Smith, Mezger & Biermann (1978) for which the Lyman continuum output indicates multiple O-type stars are present ($> 10^{50}\,s^{-1}$).

Near-infrared imaging has revealed dense, rich clusters of new born stars in nearly all of the GH II regions surveyed so far. Figure 1 shows a representative subset of the clusters imaged to date. The majority show a combination of complex nebular emission, regions of high and variable extinction, and centrally concentrated clusters of stars. A notable exception is W 49 (not shown). Only UCH II regions are seen toward the core of W 49, with several near-infrared coun-

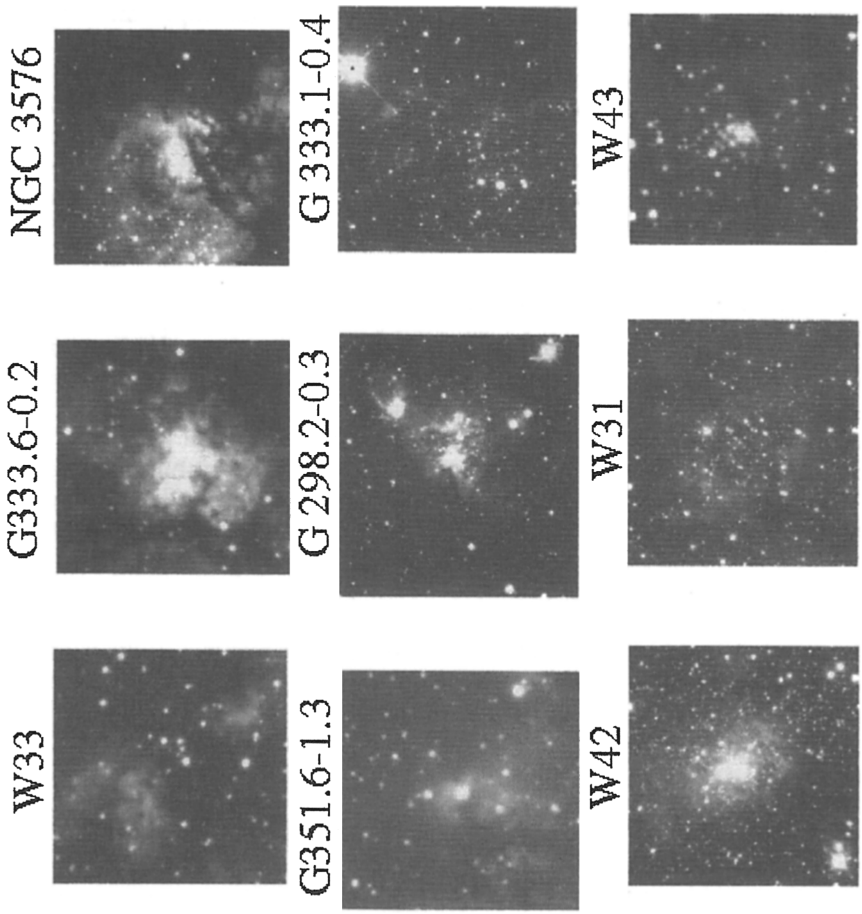

Figure 1. A representative sample of *JHK* three-color images for survey clusters. The clusters can serve as a loose 'evolutionary' sequence. The OB stars in W 33 and G 333.6–0.2 are still highly veiled, while those in W 43 have emerged and show normal IR spectral types — one of WN7 type: WR 121a.

terparts. W 49 is discussed at length by Conti & Blum 2002a,b. Figure 1 may be thought of as a rough 'evolutionary' sequence in the sense that the GH II regions to the upper left (W 33, G 333.6–0.2) are still very much embedded and so probably younger. The near-infrared point sources are still highly veiled by the hot dust from their birth cocoons that no photospheric features have been detected in the candidate O-type stars. To the lower right (*e.g.*, W 43) the clusters have become more revealed and individual stars have well determined spectral types. The brightest object in W 43 is a Wolf-Rayet type star (WN7, WR 121a in van der Hucht 2001) which suggests an age $\gtrsim$ 2 Myr (Blum *et al.* 1999); though such objects may actually be younger and hydrogen burning (*e.g.*, Drissen *et al.* 1995).

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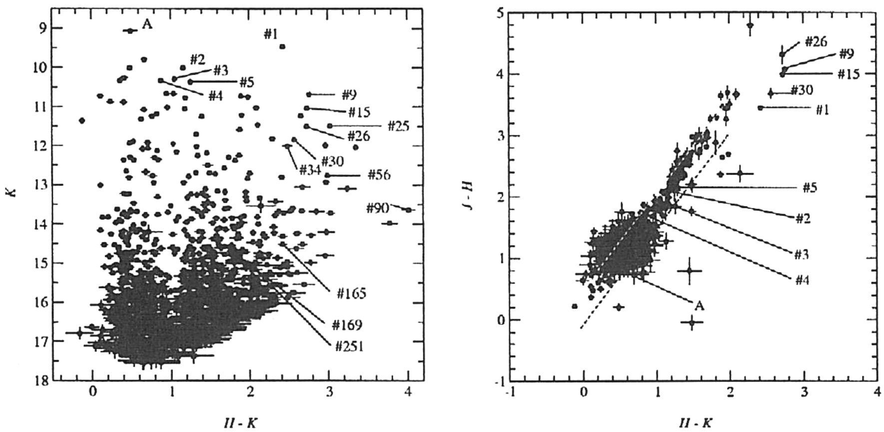

Figure 2. $H-K$ color-magnitude diagram and $J-H$ *vs.* $H-K$ color-color plot for the W 31 cluster and surrounding field. The stars labeled #2-5 are O-type stars. Stars labeled #1, 9, 15, 26, and 30 are massive young stellar object candidates. The remaining labeled objects are candidate counterparts to 5 GHz radio sources.

Intermediate clusters such as W 42 and W 31 have main sequence O-type stars (Blum *et al.* 2000, 2001) which are very young. It is clear that selecting GH II regions by their Lyman continuum output generally biases the survey to the youngest emergent clusters since the associated nebulosity has not yet had time to have been dispersed by the energetic winds and radiation pressure from the hot stars. This means that somewhat older, even luminous clusters could go undetected. Indeed the massive Arches cluster (Nagata *et al.* 1995; Cotera *et al.* 1996; Figer *et al.* 1999) would not have been found in our present survey.

A typical color-magnitude diagram (CMD) and color-color plot are shown in Figure 2. These particular diagrams are for W 31, but the basic features are common to the GH II region clusters in general. The main features are a foreground sequence at bluer $H-K$, a cluster sequence to the red, strong differential reddening which produces a larger scatter in $H-K$ than the typical photometric uncertainty, and a sequence of stars with an indicated excess of emission in $H-K$ in the color-color plot. These objects lie to the red in this diagram compared to stars whose colors are consistent with 'normal' stellar colors seen through a column of dust (some combination of interstellar and local).

The presence of these 'excess' objects is particularly exciting because it allows us to investigate aspects of the massive star birth process; their presence also strongly suggests that revealed O-type stars are on, or nearly on the ZAMS (Hanson *et al.* 1997; Blum *et al.* 2000, 2001). For all the clusters associated with GH II regions for which a $J-H$ *vs.* $H-K$ diagram exists and for which some massive stars are conclusively identified by spectroscopic means, there exist young (*e.g.*, UCH II) or pre main sequence objects, or both. It appears that the hottest O-type stars in M 17 (Hanson *et al.* 1997) have blown away

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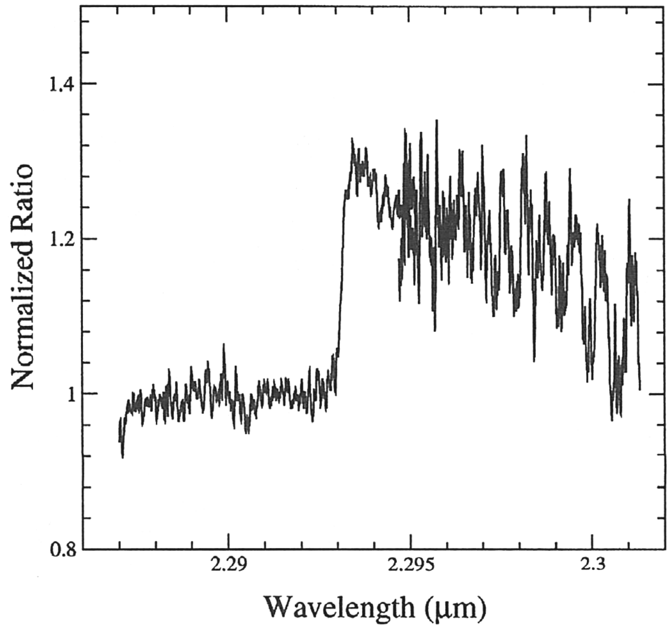

Figure 3. Gemini-PHOENIX high resolution ($R = 50\,000$) spectrum of NGC 3576 IRS1-48 at the 2.3 μm CO bandhead. The bandhead shows little broadening as might be expected for a disk. This is similar to the BN object.

their natal material, while the less massive later O- and B-type stars show clear disk signatures: CO emission and double lined profiles at Pa-δ.

These two groups are spatially segregated in M 17. At least one object in NGC 3576 also exhibits CO emission at 2.3 μm; this is typically taken as a sign of a Keplerian disk in low mass stars (Carr 1989; Carr *et al.* 1993). For higher mass stars, it is not clear that CO emission must arise in a disk. For the BN object, high dispersion spectroscopy does not reveal the expected broadening of the CO lines (Scoville *et al.* 1983) predicted for a disk origin. Scoville *et al.* prefer a model in which the CO emission arises in a spatially compact, but removed (from close to the central massive star) region, like a shock. A recent Gemini-PHOENIX high resolution spectrum of NGC 3576 IRS1-48 shows narrow CO emission as well (see Figure 3). While projection effects can not be ruled out, a disk origin in more massive YSOs may not be the rule for CO. On the other hand, the CO emission sources in M 17 have independent disk confirmation by Pa-δ spectra which show double peaked morphology. No high resolution CO spectra exist for these sources.

W 31 has a YSO which is brighter than the early O-type stars. Its spectrum exhibits permitted Fe II emission which Blum *et al.* (2001) take as evidence of a dense circumstellar flow or disk. Accounting for the larger circumstellar extinction and excess emission for this star, Blum *et al.* show (assuming the excess arises in a disk geometry) that it is most likely consistent with a late O- or early B-type star. This object is also associated with an UCH II radio

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source (Ghosh *et al.* 1989). The Lyman continuum output derived from the radio emission is consistent with the late O- early B-type classification. A similar result holds for the brightest K-band source in NGC 3576 (Figuerêdo *et al.* 2002), in W 49 (Conti & Blum 2002a), and perhaps in G 351.6–1.3. All these objects are the K-band brightest sources, have permitted Fe II, and steeply rising near-infrared continua. Were the data exist, each is associated with an UCH II region.

No mid to early O-type star (*i.e.*, one of the most massive type) has been found in any of the youngest clusters which shows evidence of a circumstellar disk. All such stars have formed recently in the presence of somewhat lower mass OB stars, some of which show unmistakable signs of disks. It is possible that the earliest stars are simply more efficient in removing their circumstellar material, and the disk phase is thus shorter. On the other hand, if the timescale for formation of the massive stars is similar to that for the lower mass stars as has been recently suggested (within 10%, Behrend & Maeder 2001) and these stars have formed at the same time, then the observations might suggest that the most massive stars do not form with associated disks.

A number of CO absorption objects have been found 'embedded' in GH II regions (NGC 3576, Figuerêdo *et al.* 2002; W 31; G 351.6–1.3; M 17, Hanson *et al.* 1997). For such objects with an associated near-IR excess emission, it is tempting to classify them as FU-Ori type. These are a rare form of YSO (Hartman & Kenyon 1996) where the disk dominates the emission and has vertical structure which produces an atmosphere like a late type star. An alternate possibility is that for very young clusters, the CO absorption is due to PMS low mass stars (*e.g.*, K-type dwarfs) which can be several magnitudes brighter than normal (M. Meyer, private communication). This latter possibility has severe implications for computing IMFs from photometry alone, but offers a novel mode of dating clusters less than 1 Myr old.

The hot star spectra obtained in these young clusters are not just useful for studying the star birth process. With suitable calibrations, they can be used to determine spectrophotometric distances to the GH II regions effectively probing Galactic structure. The details of our technique are given in Blum *et al.* (2001). Briefly, the infrared spectra are used to determine an associated spectral type and absolute magnitude. The apparent brightness and extinction are known from the *JHK* photometry and a distance is determined from the intrinsic and observed brightness. The largest uncertainty is due to the intrinsic scatter in the known brightnesses of the O-type stars (Vacca, Garmany & Shull 1996) and the unknown age of the O-type stars. The former can be improved upon by maximizing the number of stars in a cluster with individual distances determined, the latter by observing fainter B-type stars which can't have evolved off the main sequence appreciably.

Space prevents a fitting description of the on-going work at mid-IR wavelengths in these young clusters. However the promise of large telescopes and their angular resolution and sensitivity is great for elucidating the earliest phases of massive star birth. Figure 4 shows an N-band image of NGC 3576 (Leandro *et al.* 2002). Mid-IR spectral energy distributions may aid in determining the intrinsic properties of buried massive stars and/or the geometry of their circumstellar emission. The brightest source in this image is not the luminous $K-$band source IRS1-48 discussed above, but an even more buried object.

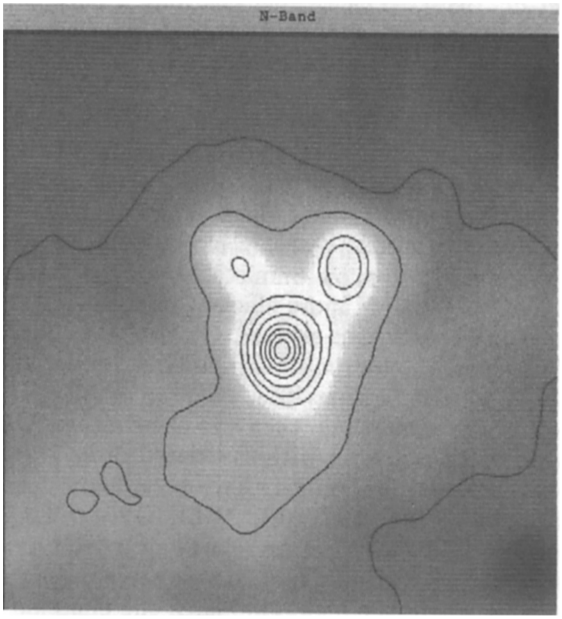

Figure 4. Gemini-OSCIR N-band ($10\,\mu$m) image of NGC 3576. This $11'' \times 11''$ image has North up and Eeast to the left. The source to the upper right (NW) is IRS1-48 whose $2.3\,\mu$m spectrum is shown above in Figure 3. IRS1-48 is the K-band most luminous source in the cluster, but it is not the brightest mid-IR object.

4. Summary

The observational basis for the emergent star birth properties of massive stars in clusters is growing rapidly through the application of near infrared techniques to individual clusters in the Galaxy. Clusters with a few to more than 100 OB stars have been identified and detailed spectra obtained for the brighter members.

Young stellar objects (YSO) are found in essentially all these young massive star forming regions. The analogous high mass objects to the lower mass YSOs are UCH II regions: OB stars which are burning hydrogen, unlike low mass YSOs, but which have not yet revealed their photospheres. A number of these, as well as more revealed OB stars, show evidence for circumstellar disks. Thus, at least some massive stars appear to form through a process which includes a disk accretion phase. However, the most massive O-type stars revealed in the young clusters do not show evidence for disks. The disk phase may be too short to observe in the most massive stars, or perhaps it does not occur.

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References

Behrend, R., Maeder, A. 2001, A&A 373, 190

Blum, R.D., Ramond, T.M., Conti, P.S., Figer, D.F., Sellgren, K. 1997, AJ 113, 1855

Blum, R.D., Damineli, A., Conti, P.S. 1999, AJ 117, 1392

Blum, R.D., Conti, P.S., Damineli, A. 2000, AJ 119, 1860

Blum, R.D., Damineli, A., Conti, P.S. 2001, AJ 121, 3149

Brandl, B., Brandner, W., Eisenhauer, F., *et al.* 1999, A&A (Letters) 352, L69

Carr, J.S. 1989, ApJ 345, 522

Carr, J.S., Tokunaga, A.T., Najita, J., *et al.* 1993, ApJ (Letters) 411, L37

Conti, P.S., Blum, R.D. 2002a, ApJ 564, 827

Conti, P.S., Blum, R.D. 2002b, in: P.A. Crowther (ed.), *Hot Star Workshop III: The Earliest Phases of Massive Star Birth*, ASP-CS 267, 297

Cotera, A.S., Erickson, E.F., Colgan, S.W.J., *et al.* 1996, ApJ 461, 750

Drissen, L., Moffat, A.F.J., Walborn, N.R., Shara, M.M. 1995, AJ 110, 2235

Dutra, C.M., Bica, E. 2001, A&A 376, 434

Eenens, P.R.J., Williams, P.M., Wade, R. 1991, MNRAS 252, 300

Figer, D.F., McLean, I.S., Najarro, F. 1997, ApJ 486, 420

Figer, D.F., Kim, S.S., Morris, M., *et al.* 1999, ApJ 525, 750

Figuerêdo, E., Blum, R.D., Damineli, A., Conti, P.S. 2002, AJ 124, 2739

Fuchs, Y., Mirabel, F., Chaty, S., Claret, A., *et al.* 1999, A&A 350, 891

Genzel, R., Hollenbach, D., Townes, C.H. 1994, Rep. Prog. Phys. 57, 417

Ghosh, S.K., Iyengar, K.V.K., Rengarajan, T.N., *et al.* 1989, ApJ 347, 338

Hanson, M.M., Conti, P.S., Rieke, M.J. 1996, ApJS 107, 281

Hanson, M.M., Howarth, I.D., Conti, P.S. 1997, ApJ 489, 698

Hanson, M.M., Rieke, G.H., Luhman, K.L. 1998, AJ 116, 1915

Hartmann, L., Kenyon, S.J. 1996, Ann. Review Astron. Astrophys. 34, 207

Henning, T., Feldt, M., Stecklum, B., Klein, R. 2001, A&A 370, 100

Hillenbrand, L.A. 1997, AJ 113, 1733

Hillenbrand, L.A., Carpenter, J.M. 2000, ApJ 540, 236

Hodapp, K.W., Davis, C.J. 2002, ApJ 575, 291

van der Hucht, K.A. 2001, New Astron. Reviews 45, 135

Kaper, L., Bik, A., Hanson, M.M., Comerón, F. 2002, in: P.A. Crowther (ed.), *Hot Star Workshop III: The Earliest Phases of Massive Star Birth*, ASP-CS 267, 95

Knödlseder, J. 2000, A&A 360, 539

Leandro, C., Damineli, A., Blum, R.D., Conti, P.S. 2003, in: J.M. De Buizer (ed.), *Galactic Star Formation Across the Stellar Mass Spectrum*, ASP-CS in press

McCaughrean, M.J. Stauffer, J.R. 1994, AJ 108, 1382

Morris, M. Serabyn, E. 1996, Ann. Review Astron. Astrophys. 34, 645

Nagata, T., Woodward, C.E., Shure, M., Kobayashi, N. 1995, AJ 109, 1676

Okumura, S., Mori, A., Nishihara, E., Watanabe, E., Yamashita, T. 2000, ApJ 543, 799

Okumura, S., Mori, A., Watanabe, E., Nishihara, E., Yamashita, T. 2001, AJ 121, 2089

Scoville, N., Kleinmann, S.G., Hall, D.N.B., Ridgway, S.T. 1983, ApJ 275, 201

Smith, L.F., Mezger, P.G., Biermann, P. 1978, A&A 66, 65

Vacca, W.D., Garmany, C.D., Shull, J.M. 1996, ApJ 460, 914

Watson, A.M. Hanson, M.M. 1997, ApJ (Letters) 490, L165

Zinnecker, H., McCaughrean, M.J., Wilking, B.A. 1993, E. Levy & J. Lunine (eds.), in: *Protostars and Planets III* (Tucson: University of Arizona Press), p. 429

Zinnecker, H., Brandl, B., Brandner, W., Moneti, A., Hunter, D. 1999, in: Y.-H. Chu, N.B. Suntzeff, J.E. Hesser & D.A. Bohlender (eds.), *New Views of the Magellanic Clouds*, Proc. IAU Symp. No. 190 (San Francisco: ASP), p. 222

Discussion

LEITHERER: How far down can you push the faint end of your CMD's? We know quite a bit on the high-mass IMF, but comparatively little on the low-mass end. It is the low end that matters for the calibration of luminosity-based star-formation rate indicators in starburst galaxies.

BLUM: These clusters are not photon limited, generally, at the low mass end. Rather, they are crowding limited. We need to go to high angular resolution with AO on 8m telescopes. We will be doing this and pushing the complete census below a solar mass in many clusters.

KAPER: Do you have an indication of the age range of the (giant) H II regions in which you find YSOs? Do the older H II regions not include YSOs?

BLUM: Due to the presence of young stellar objects and large amounts of gas an dust still present, we think the clusters must be young, less than 1 Myr. But we have no precise age determinations.

KIDGER: You show a 10 μm image of NGC 3576 IRS1-48 which looks to be much lower resolution than the accompanying K-image. I would expect the 10 μm image to be diffraction-limited. How was this image taken? The rather low apparent resolution is surprising.

BLUM: These are Gemini-OSCIR images. The maps I showed have been smoothed slightly by deconvolving them according to a standard slow PSF. While diffraction-limited images are not rare, the seeing for this run may not have been particularly good..

FELDMEIER: Janet Drew suggested a few years ago that in newly forming O- or B-type stars, the stellar radiation field may reheat the accretion disk or may be reflected from the disk. Could that be the reason why one does not find disks around young O- and B-type stars?

BLUM: That is a very interesting suggestion. We would have to understand what the effect on near-infrared colors would be. How hot does the disk have to be to hide excess emission?

ZINNECKER: Bob, that was an excellent review on the subject! While your focus was on the massive stars, you also mentioned in passing pre-main-sequence stars. In this context, let me advertise the review paper we wrote 10 years ago (Zinnecker, McCaughrean & Wilking 1993, in: Protostars & Planets III, p. 429), where we showed some of the first near-IR array images of embedded young star clusters, emphasizing the pre-main-sequence population of low-mass stars (co-spatial with the massive stars) and the interpretation of their pre-main-sequence K-band luminosity function.

BLUM: Thank you, Hans. We will certainly want to compare the results for clusters with low mass star-formation to the GH II regions.