Origin of the Peculiar He I Stars

Peter Tamblyn, Fulvio Melia, & G. H. Rieke

Steward Observatory, University of Arizona, Tucson, AZ 85721 USA

Abstract. The luminosities of the central emission stars are compared to Galactic and LMC samples. The absence of similar populations in M31 and M32 suggests they are a transient feature (Rieke & Rieke 1994). Models of extended star formation episodes can reproduce the gross features of the population (cf. Krabbe et al. 1995), but not so many very luminous emission stars. Various clues, including the stars' spatial distribution, suggest that unusual stellar development may alter the population. We have examined numerous steady-state and post-starburst models incorporating unique features of the region. Interactions of massive stars with one another, with Sgr A*, and with the mass dominating population are unlikely to influence the population substantially.

1. Introduction

With improved spatial resolution, the broad He I 2.058 μm emission line observed from the central stellar cluster (Hall et al. 1982) has been tied to individual blue, luminous stars (Krabbe et al. 1991; Krabbe et al. 1995; Tamblyn et al. 1996), including the bright components of IRS 16. Comparisons of the spectra of these sources with other luminous stars (Allen et al. 1990; Najarro et al. 1994; Libonate et al. 1995; Blum et al. 1995; Krabbe et al. 1995; Tamblyn et al. 1996) and detailed atmospheric models (Najarro 1995) have prompted comparisons to Wolf-Rayet, Ofpe, and Luminous Blue Variable stars. However, conflicts with the predictions of evolving starbursts and with a broad sample of luminous stars have led to doubts that this population represents a normally evolving, young starburst with a normal initial mass function (Tamblyn & Rieke 1993; Tamblyn et al. 1996). We consider various unique conditions in the central parsec and show that none of them are capable of modifying the evolution of a normal starburst to reproduce the observed population.

2. Are These Stars Expected?

Individually, the bright emission-line sources appear similar to some evolved massive stars, although the 2.058 μm feature is uncommon even among this class. The population seen in the central parsec appears more biased towards this emission feature than the populations in the neighboring star formation regions studied by Figer et al. (1995) and Cotera et al. (1996). The He I emission puts a lower limit on the stars' luminosities because stars cooler than 15,000 K do not exhibit this feature in strong emission. Without resorting to detailed models, the near-infrared brightness of IRS 16NE and this limit on $T_{\rm eff}$ imply that its luminosity must be at least $10^6\,{\rm L}_\odot$. Similarly, allowing the temperature to be a free parameter between 15,000 K and 35,000 K, the NIR brightnesses of the other emission sources define loci in the HR diagram. Comparisons to luminous stars in the Galaxy and the LMC (Figure 1) show that the GC stars are among the most extreme stars known. It is highly improbable that many of the Galaxy's most extreme stars would be in this sub-parsec region unless there is a mechanism in this region to prefer such stars. Our conclusions are strengthened if we make use of the stellar models of Najarro (1995; and this conference) which assign temperatures of 22,000 to 24,000 K to the most luminous three stars, requiring all three to have luminosities in excess of $10^6\,{\rm L}_\odot$. Note that Blum et al. (1995) conducted a similar analysis but came to different conclusions because they assumed the GC stars have strong IR excesses, which appears to be incompatible with their photometric colors.

The population can also be compared to the stars expected from a star formation episode (Tamblyn & Rieke 1993; Schaerer 1994; Krabbe et al. 1995; Tamblyn 1996), making use of the global constraints on the luminosity and ultraviolet radiation. Figure 2 shows the region of the HR diagram occupied by the brightest IRS 16 sources is rarely approached by evolutionary models and then only by rapidly evolving stars. The population of red supergiants (RSGs) is also readily seen to exist only in older bursts. No single burst age is expected to provide both types of luminous stars simultaneously, nor so many very luminous warm stars. Although the evolution of very massive stars is poorly understood, this conclusion seems robust to the remaining uncertainties and is consistent with the empirical comparison described above. These models also indicate uncomfortably tight constraints on the ages of the emission stars. It seems unlikely that we are fortunate enough to catch so many stars in a short evolutionary stage.

As presented by Rieke & Rieke (1994), we know enough about these stars to extrapolate to their appearance in visible wavelengths. In aggregate, we can compare with the populations in nearby galaxy nuclei where the individual stars are unresolvable. Assuming only that they are at least as hot as A stars, the cluster of emission stars produces at least 100 times as much blue light as any centrally confined populations in M31 or M32. This indicates that this stellar population is not common to galactic nuclei; it may result from an unknown feature of the GC which is different from the nuclei of M31 and M32 or it may be a transitory feature. Recent work by Massey (1996) indicates that the nucleus of M33 has characteristics reminiscent of LBV stars and may be similar to the GC.

3. Possible Origins

We have considered explanations for the central cluster beyond a normally evolving starburst to account for the large number of uncommon stars.

The extreme luminosities of the sources are easier to understand if they are compact sub-clusters rather than single stars. Indeed, IRS 13 and the IR source near Sgr A* have been shown to be such clusters (Eckart et al. 1993; Eckart

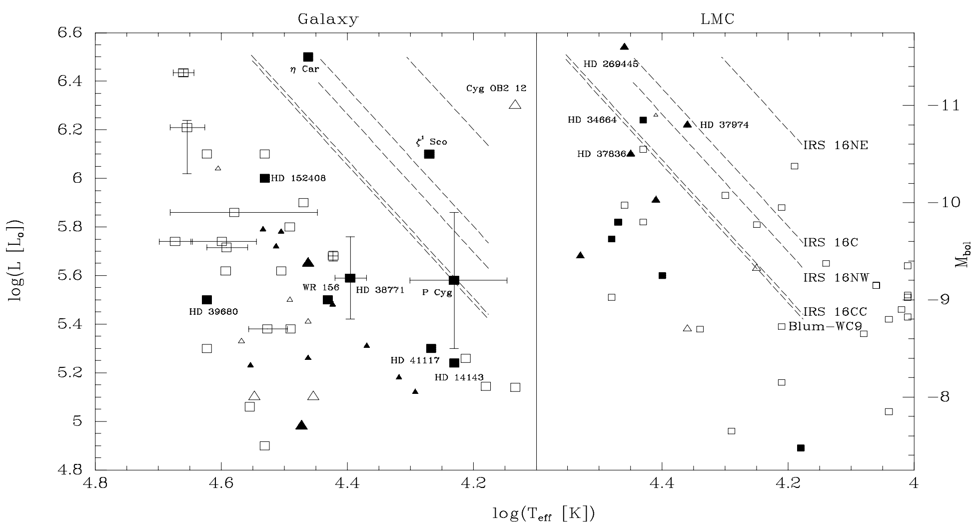

Figure 1. Luminous Galactic (left) and LMC (right) Emission-Line Stars Compared to the He I Emission Sources. The dashed lines are the loci near which several of the GC sources must lie. They have been labeled only in the right panel to reduce clutter. Filled symbols are comparison stars with the He I 2.058 μm emission line; open symbols are stars without the line or with only absorption in the line. Squares are used when both $T_{\rm eff}$ and L are available from the literature; small triangles are used when both had to be estimated from spectral type; large triangles are used when one had to be estimated. Error bars are indicated where available or where the literature has discordant values. The LMC stellar parameters are from McGregor et al. (1988). The IRS 16 luminosities assume blackbodies at a distance of 8 kpc with $A_K = 3.47$. Both vertical axes apply to both panels.

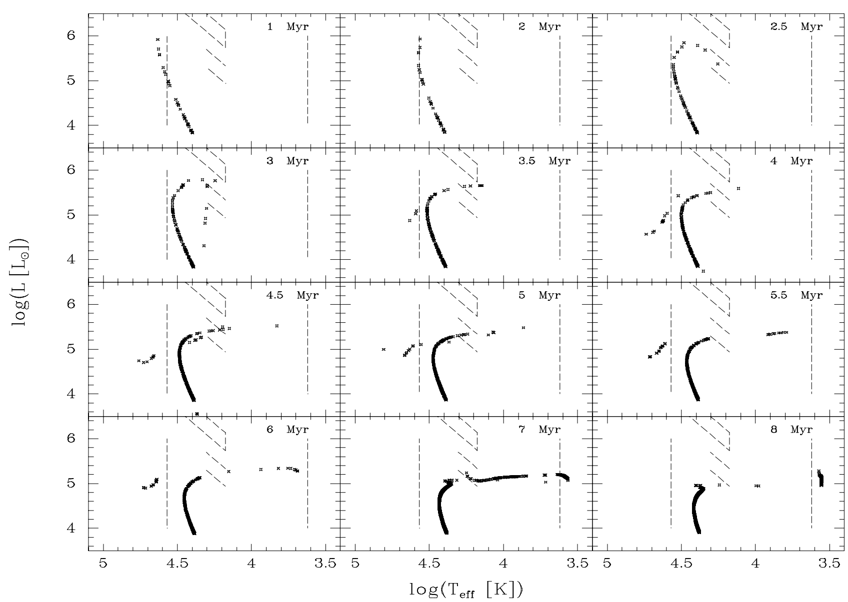

Figure 2. HR Diagrams of Synthetic Bursts. The source tracks for these randomly populated bursts are from Meynet et al. (1994) for Z=0.04 and enhanced mass loss. The dotted lines at $T_{\rm eff} = 4,170$ and 37,000 K represent the regions of RSGs and the UV constraint. The rhombus is the location of the brighter He I sources with the cool edge at 15,000 K and top and bottom at $m_K = 8.8$ and 9.8 (d= 8 kpc, $A_K = 3.47$). Line segments at $m_K = 10.8$ and 11.8 (background) are also indicated for reference. Note that no stars are ever expected to match IRS 16NE well and that stars approach the region required to match IRS 16C,CC,NW, etc. only in bursts with ages ~ 3 Myr but that RSGs do not develop for quite some time later. Also note the large number of O stars near the main sequence expected for young bursts and that they are fainter at K than the $1''$ seeing background.

this conference). However, the lunar occultation measurements (Simon et al. 1990; Simons et al. 1990) show that the dominant components of several of the brighter IRS 16 components are smaller than 200 AU. The detection of the 2.058 μm He I emission line from these sources is further evidence that they are dominated by a single star because stars with strong emission in this line are very luminous but shortlived, and there is no population of similarly bright hot stars without He I emission in the region.

Models in which the population of emission stars is maintained at present numbers have the appeal of not implying any fortuitous coincidence in observing these stars in a transitory state. One such model for the luminous sources presented by Morris (1993) is that the luminous sources are non-stellar accretion objects. However, this model requires instead some otherwise unknown feature to differentiate the nucleus of our galaxy from those of M31 and M32, as it is not obvious why such a steady-state population would not also be seen in those nuclei. A second steady-state model is that the luminous sources are the products of stellar mergers. However, several of the sources are now known to have luminosities of order $10^6\,L_\odot$, and hence must have masses well over $30\,M_\odot$. The stellar merger process in this environment is far too slow to build up appreciable numbers of such massive products (Lee 1993).

3.1. Persistent Star Formation

Some of the difficulties with single-age burst models are avoided by considering a star formation event which is extended slightly in time (cf. Krabbe et al. 1995). Specifically, one can imagine that the current RSGs are slightly older than the most luminous blue stars. However, some constraints remain. The recent level of star formation must be substantially reduced from that of a few Myr ago or the youngest stars would provide a hotter UV radiation field than that which dominates the region. Further, the comparison samples show that the emission stars are a minority of late-OI stars. Hence, they would be expected to be accompanied by bright blue sources without the He I emission feature, but these are not present in the central parsec. Hence, although introducing the free parameter of a time-variable star formation rate can significantly improve the fit of burst models with the gross properties of the observed cluster, the observed bias for He I emission would not be expected from any star formation history.

3.2. Unusual Evolution

Various features of the central parsec are unique in the Galaxy and might influence stellar evolution. Processes which can hasten the mass loss experienced by the most massive stars would be expected to expose the enriched inner regions earlier in the stellar life cycle, greatly increasing the fraction of a massive star's life in which it could exhibit helium emission features.

The central cluster has often been suspected of having super-solar metalicity. Increased atmospheric opacities would be expected to enhance the stellar mass-loss winds and super-metal-rich stellar evolution might be substantially different than that observed elsewhere in the Galaxy. However, the gas from which these stars formed has modest metalicity (Shields & Ferland 1994) and the best studied star, IRS 7, also has a metalicity near solar (Carr, this conference).

Interaction with a massive central object (Sgr A*) could strip material from an extended RSG, but the tidal radius for such an interaction is only 0.002 pc, and it is implausible that such a high fraction of the massive stars currently seen in the central 1/2 pc were this close to the central object during their late evolutionary phases.

Massive stars can influence one another if sufficiently close through direct mass exchange or stripping by winds or supernova ejecta (cf. Podsiadlowski et al. 1992, Livine et al. 1992). However, the separations at which these processes have been shown to be important are more typical of tight binaries than of the distances seen between the massive stars in the GC. Energy considerations alone are sufficient to show that the known massive stars have minimal impact on one another through stripping by stellar winds or supernovae.

The extreme space density of (unseen) low-mass stars or remnants implied by dynamical mass estimates differentiates the central parsec from even the neighboring star formation regions. Current limits permit a central density well over $10^7\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$. In such an environment, an extended RSG will experience frequent collisions, some fraction of which can result in core ejection or tidal capture. Core ejection is a mechanism proposed by Tuchman (1985) in which the condensed core of an extended star is yanked from the dynamically slower envelope by the gravitational tug of a passing star or remnant if the imparted kinetic energy exceeds the core–envelope binding energy,

$$\Delta E_c = \frac{2G^2 M_c m^2}{v_r^2 b^2} \gtrsim 1.7 \times 10^{48}\,\mathrm{erg}. \tag{1}$$

The exposed core of a RSG would be expected to have many observational features in common with a Wolf-Rayet star. However, plunging collisions with $b \lesssim 10\,\mathrm{R}_\odot$ are required, and we find that such collisions are far too uncommon to explain the observed population (Tamblyn 1996). Tidal capture is a process by which a passing star can be trapped in a very tight orbit (Fabian et al. 1975). Subsequent evolution of the primary can then drive the secondary into contact with the primary's envelope. Simulations (e.g., Taam & Bodenheimer 1991) show that substantial envelope material can be ejected from such a system by conversion of binary orbital energy. With Max Ruffert, we have conducted simulations of this capture mechanism appropriate for the conditions in the GC and find that this process is inefficient in this kinetically hot system. The timescale on which a $15\,\mathrm{M}_\odot$ RSG with radius $400\,\mathrm{R}_\odot$ is expected to capture companions is

$$\tau = 420 \left(\frac{n_*}{10^7\,\mathrm{pc}^{-3}}\right)^{-1} \left(\frac{m}{1\,\mathrm{M}_\odot}\right)^{-1.1} \left(\frac{\sigma_v}{140\,\mathrm{km/s}}\right)^{3} \mathrm{Myr}, \tag{2}$$

far too slow to have a substantial impact on this cluster (Tamblyn 1996).

3.3. Unusual Formation

Conditions in the central regions might also lead to unusual star formation as discussed by Morris (1993) and by Zinnecker (this conference). It may be that the inital mass function is severely skewed relative to what is seen in other regions, favoring the most massive stars. Alternatively, massive stars might preferentially form in tight binaries in which some of the processes described above can operate fast enough to influence the appearance of evolved massive stars. Further research in this direction is likely to benefit from consideration of other regions where star formation has occured in unusually dense regions. The dense cores of 30 Dor and NGC 3603 have recently been probed with *HST* and they have some characteristics in common with the central parsec of the Milky Way. The latter has a Wolf-Rayet fraction which increases in the densest regions and both have late-WN stars in tight binaries. Further, NGC 3603 also has 6 O3V-III stars (Drissen et al. 1996). These are generally thought to be precursors to the Wolf-Rayet stars seen in the coeval cluster. This suggests that age is not the distinguishing factor and that a second influence has driven some stars to appear as Wolf-Rayet stars at an early age.

4. CO-Depletion Region

Although the tidal capture mechanism has been shown to be too inefficient in this region to influence substantial numbers of massive stars, less massive stars have substantially longer lifespans. For a low-mass main-sequence star, the estimated timescale for capture of a companion into a tight orbit is 20 Gyr if the density of stars and remnants is $10^7\,\mathrm{pc}^{-3}$. The subsequent evolution of such a system is likely to inhibit the red giant phase of the primary. *HST* observations of globular clusters will allow quantitative tests of this hypothesis. In the GC, the expected consequence would be a region in which many of the low-mass stars have their envelopes ejected as they evolve to larger dimensions, especially in the densest central regions. This could explain the observed CO-depletion region (Sellgren et al. 1987) and provides additional detail on how stellar collisions may be responsible for this feature.

5. Conclusions

We have seen that the emission-line stars in the central parsec are problematic as a normal starburst population even though they have individual analogues among massive evolved stars elsewhere in the Galaxy. Comparison with the nuclei of M31 and M32 illustrate that the GC is either unique in its ability to sustain a population of luminous blue sources, or is in a time-dependent phase. Expected influences of the conditions in the central region are not sufficient to explain the unusual appearance of so many massive stars, but unusual star formation, such as a very top-heavy initial mass function or large fraction of tight binaries, may explain the development of such a cluster from a recent star formation episode.

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