CHAPTER 6

UNUSUAL STELLAR EVOLUTION

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Abstract

The stellar population at the GC may arise from unusual stellar development unique to this region. Steady-state and time-dependent models of the influences of unique characteristics of the region are reviewed and developed. Most are rejected as either quantitatively implausible or equally applicable to the nuclei of M31 and M32, neither of which has a blue stellar population like the one in the GC. Most promising are a class of models with time dependence provided by star formation in the recent past. Interactions of the massive stars with one another, with Sgr A*, and with the mass-dominating population are unlikely to influence the population substantially. We speculate that the high stellar densities might alter star formation to increase the number of tight binaries or very massive stars. Tidal capture by low-mass stars may explain the central CO depletion region.

6.1 Introduction

In the previous two chapters, we found that the central 1/2 pc has a large number of luminous, warm stars. Some of these stars, (Blum-WC9 and AF) and probably most of the faint, wide-lined stars, are WR or very closely related stellar types. The remainder are probably also enriched and all have evolved off the main sequence. Similar populations are not seen in the nuclei of M31 or M32 (Section 5.2). Single-burst models are unable to produce these stars and the observed RSGs (Krabbe *et al.* 1995; Section 5.4). The stellar content of young clusters is consistent with this conclusion. Persistent- or double-burst models can reproduce the gross properties of the population, but several difficulties remain. First, without a physical motivation, it seems contrived to have had two recent star formation episodes, especially considering the region's current hostility to star formation (cf. Morris 1993). Second, the normal-burst models depend on an almost complete association of luminous, warm stars in the models with He I stars, but our comparison sample illustrates that He I emission is a rare characteristic even among luminous emission-line stars of the appropriate temperatures. Third, the GC population contains an anomalously large number of stars significantly more luminous for their effective temperatures than the members of an extensive comparison sample. These stars bring into question the ability of any sequence of normal star formation followed by normal evolution to match the GC population. Fourth, the burst scenario does not obviously explain the observed concentration in the central 1/2 pc. Not only is the spatial density of the emission-line stars much higher in the IRS 16 environs, but there is an apparent correlation of location with continuum and emission properties (Section 5.6). Specifically, the IRS 16 components are the brightest spatially unresolved He I stars and they have narrow line widths in contrast to the outlying members (AF, AHH-NW, IRS 15NE...) which are fainter and have broader emission lines. These factors lead us to consider alternative hypotheses which depend on the region's unique characteristics.

6.2 Steady-State Models

The expectation that we are not viewing the nucleus of our galaxy at a special time is a strong argument in favor of steady-state models or cyclic models in which the period is much shorter than the age of the Galaxy. Several steady-state models have been proposed since the discovery of the bright sources. However, the population of bright blue sources within the central parsec of the Milky Way contrasts dramatically with the absence of such objects in the dense nuclei of other galaxies where we might expect to see them (Section 5.2). Although the Galaxy may be unique in some as yet undetected way which permanently sustains the population of blue objects, these observations argue strongly against models in which the luminous blue objects form in a steady-state process that does not require unique conditions. Several such models are briefly reviewed here in light of this new finding.

6.2.1 Ongoing Stellar Mergers

At the stellar densities implied by recent observations, $n_* > 10^7\,\mathrm{pc}^{-3}$ (Eckart *et al.* 1993; Haller *et al.* 1996; Krabbe *et al.* 1995), individual low-mass stars can repeatedly collide and merge to build up to more massive stars (Lee 1987). According to this interpretation, the bright stars seen are a steady-state population of these merger products. However, the *HST* observations of M31 and M32 rule this out for the warm stars because these nuclei do not exhibit luminous blue stars like in the GC despite otherwise similar populations and spatial distributions of stars. Krabbe *et al.* (1995) further argue that the luminosities of these sources indicate they are like the most massive stars, and stellar mergers cannot build up to such high masses during the short lifetime of the merged object. Initially, for low-mass main-sequence stars, the typical collision interval of over 10^9 yr (Eckart *et al.* 1993) restricts the growth to a rate too slow to reach the implied masses. This rate would increase as the merger product departs the main sequence and expands its cross-section, but the life expectancy of the merger product is then very short. Hence, the decreasing stellar evolutionary timescale beats out the timescale for additional mergers and restricts the product masses to well below $30\,M_\odot$. However, as discussed in Section 5.5, a comparison with the Eddington limit indicates that the brighter GC stars must have masses at least this large if built from mergers of low-mass stars with unenriched abundances. A detailed model with ongoing stellar mergers including the evolution of the cluster through core collapse (Lee 1993) shows that masses $\gtrsim 20\,M_\odot$ are seen only in smaller numbers than the observed He I stars and only for a limited time ($\approx 3 \times 10^8$ yr) around core collapse when the cluster parameters are substantially more compact than currently observed.

6.2.2 Accreting Black Holes

Morris (1993) has suggested that the bright (red) sources are powered by matter accreting onto stellar remnant black holes. He argues that through gravitational settling, the space density of these remnants would be significantly enhanced and the probability of collision with a star large. He proposes that the product of such a collision would be a luminous accretion source in which the originally stellar material puffs up to red-giant proportions in response to the high luminosity. However, this model would apply equally strongly to M31 or M32. Formation of these accreting objects through an enhanced merger rate during a time-dependent dynamical event, such as core collapse of the central cluster, would be a possible explanation, but in this case the central objects would be much more strongly concentrated within the core than are the prominent IRS 16 components (Lee 1993).

6.2.3 Clusters

The source crowding and the extreme luminosity of the brightest GC sources has led to suggestions that these stars might be tight clusters rather than single objects. Indeed, Eckart *et al.* (1993) resolve IRS 13 into 5-10 components within $1''$ diameter. However, lunar occultation data (Simon et al. 1990; Simons et al. 1990) show that the bright (at K) components of IRS 16 are dominated by point sources even with a $0\farcs02 \sim 200\,\mathrm{AU}$ scale. This is a considerably finer resolution than even the $0.15''$ achieved by Eckart *et al.* (1993). Hence, if sources such as IRS 16NE were to be sub-clusters, they would need to be much more compact than the IRS 13 group. Further, if this were the explanation for the IRS 16-like sources, we would expect to observe a large, dispersed population of individual stars with similar properties (except for brightness) which had evaporated from the sub-clusters. Although fainter, outlying He I sources have been identified, their emission line profiles are distinctly wider. Also, the equivalent widths of the IRS 16 He I emission lines are quite large compared to most of our non-WR comparison stars. Hence, it is likely that the He I sources dominate the brightness of the IRS 16 sources (excluding the extended IRS 16S). However, even the lunar occultation observations do not exclude tight ($a \ll 200\,\mathrm{AU}$) binaries in which the He I source provides at least half the near-IR flux, but this is qualitatively different from the previously popular sub-cluster interpretation and will be discussed in detail below.

6.3 Time Dependence from Recent Star Formation

Given the independent evidence for recent formation of massive stars in this region (e.g., IRS 7, Lebofsky *et al.* 1982; it's tail, Yusef-Zadeh & Melia 1992; and a nearby maser, Yusef-Zadeh & Mehringer 1995), the most promising avenue for investigation appears to be models in which the blue objects result from abnormal formation or evolution of massive stars due to the environment of the GC. According to this interpretation, the current state of the GC represents a short-lived (and possibly recurring) phase shared by other galactic nuclei. The distinction from M31 and M32 is only that they have not had recent nuclear bursts of star formation. The challenge is instead to understand what distinguishes the GC from other star forming regions.

Observationally, the distinguishing features of this population are a relatively cool integrated UV spectrum and a high concentration of very luminous stars, many of which have the uncommon trait of He I 2.058 μm emission. Various pieces of information independent of the stellar characteristics allow us to estimate the age of the star formation episode(s). Most persuasive for a very recent episode are the H_2O maser recently discovered at the intersection of the expanding [Fe III] shell with the surrounding molecular cloud (Yusef-Zadeh & Mehringer 1995) and the shell itself (Lutz *et al.* 1994). Assorted stars (IRS 7 and AF among them) also appear to be fairly normal products of a very recent star formation episode. Hence, it is fairly clear that evolved massive stars inhabit the region. However, as we showed in Chapters 2 and 5, the overall characteristics are inconsistent with the expected population from a single burst. We focus here on mechanisms suspected to increase the frequency or lifetimes of blue, evolved, massive stars.

6.4 Unusual Single Star Evolution

As briefly discussed in Section 3.4, it seems unlikely that the peculiar GC objects can be explained in terms of abnormal evolution caused by metallicity effects. This result seems to hold even if moderately elevated metallicities increase the atmospheric opacities and enhance the winds, although a better understanding of high-metallicity massive stellar evolution would be desirable. The enhanced winds would increase the duration of the WR stage. However, the gas around the GC out of which these stars must have formed does not appear to have metallicity higher than twice solar (Shields & Ferland 1994), nor is there evidence in stellar spectra for a dramatic increase in metallicity within the central kpc (Tyson 1993). Finally, the population sampled in the surrounding 40 pc (Cotera *et al.* 1995) does not appear to be anomalous.

6.5 Influences of Other He I Stars

The spatial distribution of the He I stars suggests that close proximity to one another and/or location near the dynamical center is important to their formation or evolution. The extreme stellar density in the GC may increase the importance of a number of mechanisms which can affect massive stellar evolution. Mechanisms which are unimportant elsewhere may have dominant roles in this environment. All of these would be of greatest importance to post-main-sequence supergiant stars despite their comparative rarity (short evolutionary stage compared to main sequence) because they have much more distended and hence less tightly-bound atmospheres than do main-sequence stars. Although the observed spatial distribution suggests that location may be a dominant factor in determining whether a RSG is influenced, the proximity of several RSGs (IRS 7, IRS 9) indicates that the mechanism may operate on a timescale comparable to the RSG phase. Specifically, any mechanism suggested to create the anomolous concentration in the GC from normal RSGs must have a timescale shorter than a typical RSG lifetime to account for the relative excess of these stars, yet not so short as to make the presence of RSGs in the region troublesome.

If RSG envelopes are preferentially stripped, this would account for an enhanced number of hot, luminous stars similar to the fainter He I sources; the bright IRS 16 sources are apparently too luminous to have ever experienced a RSG phase. The luminosity of a massive, core-helium-burning RSG would not be affected dramatically by the loss of most of its envelope (Arnett, private communication). The stripped object would be a hotter star, probably with somewhat enriched surface abundances. Traditional WR stars demonstrate that a massive star which has shed its envelope will be hot and luminous. Whether the resulting star appears as a WR star or more like an Ofpe/WNL star is a function of the new surface abundances: WR winds are driven by the substantially increased opacity of He-rich material. In contrast, low-mass, hydrogen-rich stars have an opacity which more closely follows Kramers Rule; the decreased temperature at the new surface layers permits ion recombination, increasing the opacity and leading to runaway expansion (Arnett; Renzini *et al.* 1992).

First we consider three consequences of the proximity of the known massive stars to one another. Although an extended envelope can be stripped by a nearby supernova (SN) if it is in a sufficiently tight binary (Livine, Tuchman, & Wheeler 1992), this mechanism is unlikely to play a significant role if the massive stars are as evenly distributed as the bright sources. The typical projected separation of the major IRS 16 components is at least 0.01 pc; hence, even a $1200\,R_\odot$ star would intercept $\sim 2 \times 10^{-6}$ of the 10^{51} ergs available in the kinetic energy of the ejecta. This would allow the liberation of less than a solar mass of envelope even from the tenuous hold of a RSG. The population models (see Figure 5.1) show that if the RSGs are from a single burst which dominates the region's UV with age ~ 6.5 Myr and a high mass IMF index of -3.3, then of order 230 supernovae should have gone off in the past few million years. If uniformly distributed through the central 1/2 pc, they would typically be ~ 0.1 pc from the nearest RSG and exert a negligible influence. Indirect indications of these supernovae would be difficult to detect in this region due to other energetic phenomena.

Similarly, although massive stellar winds carry a significant amount of energy and momentum (mass-loss rates $\sim 10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, terminal velocities $\gtrsim 1000\,\mathrm{km\ s}^{-1}$; Conti 1988), the geometrical dilution at typical separations indicates this is not likely to account for the GC He I stars. Although the radiative power produced by an O star is $\sim$ 100 times the wind power and the intercepted UV could be a substantial ionization heating source in a nearby RSG's atmosphere, it would require an unrealistically high efficiency near unity to ablate even $10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ in this manner with the expected typical separation. IRS 7's ablation by the composite UV and wind from IRS 16 (see Yusef-Zadeh & Melia 1992 and references therein) is a physical example of the process. Its mass-loss rate of $10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (Serabyn *et al.* 1991) is comparable to what would be expected without the external UV and wind sources, confirming that this process is inefficient when operating over scales $\approx 1/3\,\mathrm{pc}$.

6.6 Influences of Sgr A*

A central massive object ($M \sim 10^6\,\mathrm{M}_\odot$) associated with Sgr A* could disrupt stars which pass within a tidal radius (cf. Hills 1975)

$$r_t \sim \left(\frac{M_{co}}{M_*}\right)^{1/3} R_*. \qquad (6.1)$$

For a RSG, this is less than $10^5\,\mathrm{R}_\odot \approx 0.002\,\mathrm{pc}$. In the $10''$ (0.4 pc) around Sgr A*, there are approximately 5 RSGs and at least 9 blue stars (Rieke & Rieke 1988; Krabbe *et al.* 1991). It is unlikely that such a large fraction of the available RSGs would have passed this close to the central object during this short-lived phase. If Sgr A* strongly dominated the region's mass, it might be reasonable to propose that all these stars are on highly elliptical orbits with periastron within this radius, but the light and mass distributions do not appear to be this centrally concentrated. If space velocities of these stars, which may be obtainable in the near future, are biased in this way, this would strongly argue that the other stellar orbits are also likely to be highly eccentric, which would influence the derived mass of the central object.

A sporadic influence of a central supermassive black hole also needs to be considered. The Sgr A geometry may indicate a recent explosion near the dynamical center (Yusef-Zadeh & Morris 1987). This explosive event must have been more powerful than a typical supernova unless preceded by a strong wind (Mezger *et al.* 1989). Theoretical studies (e.g., Hills 1975; Khokhlov & Melia 1996) indicate that stars from the mass-dominating population occasionally pass within the tidal disruption radius of Sgr A*, creating large, explosive events. Although typical event energies are $\approx 2 \times 10^{52}$ ergs and these occur every $\sim 10^{4}$ yr (Khokhlov & Melia 1996), the less common but more energetic events such as may be responsible for Sgr A East are more interesting in this context. A typical RSG would experience one of the 10^{53} erg events which are expected to occur every $\sim 10^{5}$ yr because the ejecta are distributed over a solid angle $\lesssim 0.2$ steradians. At a distance from Sgr A* typical of the IRS 16 stars of ~ 0.1 pc, enough of the explosive energy to remove $\sim 0.2\,\mathrm{M}_\odot$ would be intercepted. This is inadequte to affect a RSG dramatically, and it is unlikely that all of the currently blue stars were significantly closer during one of these events.

6.7 High-Mass, Low-Mass Star Interactions

6.7.1 Space Density of Low-Mass Stars

Another possibility is that the extremely high density of low-mass main-sequence stars (and possibly stellar remnants) alters the evolution of massive stars in the

GC. Although the stellar density in this region must be very high, it is difficult to measure quantitatively, both because the light from the region is dominated by a small number of very luminous objects and because the mass is dominated by a central concentration of dark matter. As a result, it is difficult to measure either the light or the mass associated with the low-mass stars. Eckart *et al.* (1993) measure a small core radius (0.15 ± 0.05 pc) and a central mass density of $\rho_c = 10^{7.7\pm0.5}\,\mathrm{M_\odot\,pc^{-3}}$. Rieke & Lebofsky (1987) use a different technique and measure a core radius of ~ 1.2 pc for low-mass stars, which would imply a stellar density in the central 0.2 pc an order of magnitude lower than the estimate of Eckart *et al.* (1993) for the total mass density. Moreover, the number and distribution of dark objects such as stellar remnants is unknown: current limits would allow a density as high as $\rho_c = 2 \times 10^8\,\mathrm{M_\odot\,pc^{-3}}$ within the central $4''$ radius if the central dark mass is not predominantly in the form of a black hole. Hence, the space density, n_*, of main-sequence stars and more compact objects is highly uncertain and may exceed $10^8\,\mathrm{pc^{-3}}$. High stellar densities are also encountered in the cores of globular clusters, and two classes of mechanisms for stripping the envelopes from low-mass red giants in these systems have been studied. This section reviews the mechanisms of core ejection and common-envelope ejection, and indicates how they might apply to the GC region. We make estimates of the rates of these processes to determine which, if either, may play an important role in the GC.

6.7.2 Core Ejection

A consequence of collisions in which a relatively compact low-mass object (main-sequence star or stellar remnant) plunges through the envelope of a RSG can be that the dense RSG core is slingshot out of the dynamically slow envelope. This mechanism was studied in the context of red giants by Tuchman (1985) and Livine & Tuchman (1988) to explain the gas clouds observed in the GC by Lacy, Townes,

& Hollenbach (1982) (see also Davies, Benz, & Hills 1991 and Rasio & Shapiro 1991 for application to globular clusters). In the impulsive approximation, as used by these authors, the kinetic energy imparted to the core of mass M_c by the pull of the passing intruder of mass m with impact parameter b and relative velocity v_r is

$$\Delta E_c = \frac{2G^2 M_c m^2}{v_r^2 b^2}. \tag{6.2}$$

This must exceed the binding energy of the core to the envelope for ejection. For a model RSG with mass $15\,\mathrm{M}_\odot$, kindly provided by Dr. S. Woosley, this binding energy is roughly 1.7×10^{48} ergs, yielding $b_{crit} \approx 10\,\mathrm{R}_\odot$. This value is uncertain because the binding energy depends on the choice of core-envelope boundary. This result is markedly different from Tuchman's analysis primarily because the model RSG envelope profile is considerably steeper than the $\rho \sim r^{-1.5}$ for a red giant. An impulse approximation leads to a predicted interval between such close collisions for a RSG in a system with velocity dispersion σ_v of

$$\tau \gtrsim 1.3 \times 10^7 \left(\frac{n_*}{10^8\,\mathrm{pc}^{-3}}\right)^{-1} \left(\frac{\sigma_v}{170\,\mathrm{km/s}}\right)^{\alpha} \mathrm{yr} \tag{6.3}$$

in which α is just under 2. This estimate is very coarse because the freefall velocity at such small impact parameters is comparable to typical collision velocities, contrary to the impulse approximation. Nonetheless, it shows that this mechanism is unlikely to affect a large fraction of the GC RSGs during their $\sim 10^6\,\mathrm{yr}$ life spans even if $n_* \approx 10^8\,\mathrm{pc}^{-3}$, in the upper range of what is allowed by observations.

6.7.3 Common-Envelope Evolution

In a sufficiently tight binary ($a \lesssim 1000\,\mathrm{R}_\odot; P \lesssim 2.5\,\mathrm{yr}$ for $M = 15\,\mathrm{M}_\odot, m = 1\,\mathrm{M}_\odot$), the secondary is eventually engulfed by the evolving supergiant's envelope. In this subsection we review the consequences of such a structure and look at two reasons why the requisite close binaries might be more likely to exist in the GC. Throughout, we use primary and secondary to refer to the perturbed and perturbing stars, respectively.

Taam, Bodenheimer, & Ostriker (1978) showed how a neutron star companion orbiting in a RSG envelope can generate enough drag dissipation to accelerate a portion of the envelope to greater than the escape velocity. More recent work (see Livio & Soker 1988, Taam & Bodenheimer 1991, and references therein) replaced the neutron star with a low-mass main-sequence star such as would be more likely to be captured by a nuclear RSG. Although the timescales change, the envelope is still ejected efficiently on a timescale shorter than that of stellar evolution. These systems are distinguished from contact binary systems or W Ursa Majoris stars in that the binary's mass ratio is skewed so the envelope is not co-rotating with the secondary before contact (Livio & Soker 1988; Taam & Bodenheimer 1991). Hence, the secondary drags through the envelope and locally deposits orbital energy. The secondary spirals in through the envelope until it coalesces with the primary's core or until enough envelope mass has been ejected that the primary can settle within the (significantly reduced) orbit radius. The need to explain short-period evolved systems (low-mass X-ray binaries, binary radio pulsars, cataclysmic variables, and binary-nucleus planetary nebulae) has prompted increasingly sophisticated efforts to study common-envelope systems. The efficiency of orbital energy conversion for the liberation of envelope material, $\alpha_E \gtrsim 0.15$ (Taam 1993), is more than adequate to strip the envelope of a RSG. Physical effects which divert or dissipate energy, reducing α_E from unity, are envelope spin-up, acceleration of some material beyond escape velocity, and energy transport resulting in increased luminosity which is directly radiated from the system without internal conversion to mechanical energy (Taam *et al.* 1978). Although the competitions among the timescales for mass ejection, orbital decay, energy transport, and envelope spin-up are critical for determining whether the final state of the system is a short-period binary or coalescence, it has been shown for other systems (and compact evolved systems demonstrate) that most or all of the common envelope is lost. It is therefore reasonable to expect that similarly efficient envelope ejection would affect a RSG in the GC which has engulfed a low-mass secondary.

6.7.4 Tight, Coeval Binaries

In general, a large fraction of stars are formed in binaries. It is possible that this tendency is enhanced by the abnormal conditions under which stars form in the GC. The formation process may be akin to fragmentation of an accretion disk, rather than collapse of condensations from a molecular cloud. At the high densities involved, the collapsing protostars will be subject to perturbations by collisions or near misses with each other, and furthermore will have numerous interactions with the many low-mass main-sequence stars and remnants that populate the region. These perturbations could trigger instabilities that lead to enhanced binary formation in a manner analogous to the proposal of Bonnell (1994). He considers a rapidly rotating central object surrounded by a rotationally supported infalling disc of gas and shows that instability modes can cause formation of a self-gravitating secondary body in orbit around the central one.

6.7.5 Companion Capture

Due to the extreme stellar density, binaries can also be formed during the short life span of a massive star. The formation of binaries in dense stellar systems has been studied extensively in the context of globular cluster cores, and many of the same processes operate in the GC. Significant differences are introduced by the large mass ratios, large relative velocities, and short timescales relevant to the current problem. For instance, equilibrium arguments do not apply because a massive star's lifetime is shorter than the equilibration timescale. Also, because of the high velocity dispersion, conventionally defined "hard" binaries, $E_{bind} \gg m\sigma_v^2$, are considerably harder than required to evolve into a common-envelope binary. In globular clusters, the soft binaries are of minimal importance because they have a low equilibrium density and little binding energy. We cannot ignore the "soft" binaries with $1/30 \lessapprox E_{bind}/m\sigma_v^2 \lessapprox 1$ because we are interested in the evolution of the binary systems themselves rather than their impact on the cluster energetics.

In general, binaries can be formed by transferring excess relative kinetic energy to a third body. A simple density argument (Binney & Tremaine 1987, p. 492) is sufficient to show that the rate at which massive stars in the GC participate in 3-body encounters which create a binary is vanishingly small. The only binary formation mechanism we need to consider is capture by conversion of orbital energy into tidal distortions of the distended target star.

6.7.6 Tidal-Capture Rate — Analytic Estimates

In this dynamically hot system, typically only penetrating encounters (collisions) remove sufficient orbital energy through tides to create a bound system. The perturbations induced by such a collision are not well approximated by conventional estimates of tidal distortion derived for a close pass, as discussed further below. Nonetheless, we will use initally the impulsive tidal approximation to estimate the orbital energy loss, ΔE_T, in the encounter because the uncertainty in the rate at which a RSG captures companions,

$$\mathcal{R} = \tau^{-1} = n_* \int_0^\infty f(\vec{v_r})\sigma(v_r)v_r d^3\vec{v_r}, \tag{6.4}$$

is still dominated by the uncertainties in the stellar density n_* discussed earlier.

To estimate roughly the capture cross-section, $\sigma(v_r)$, we can consider the excitation of $l = 2$ non-radial oscillations in the RSG envelope as presented by Fabian, Pringle, & Rees (1975) (hereafter FPR), adapted for a distended star (Bailyn 1988). The problem has also been studied for larger impact parameters by analogy to stellar dynamical behavior (Spitzer 1987; see also Binney & Tremaine 1987, p. 438). The requirement for tidal capture can be expressed as (Davies *et al.* 1991):

$$\Delta E_T = \frac{GMM_{env}}{R} f^2 \left(\frac{m}{M}\right)^2 \left(\frac{R}{b}\right)^6 \geq \frac{1}{2}\frac{Mm}{M+m} v_\infty^2. \tag{6.5}$$

M, M_{env}, and R refer to the primary's mass, envelope mass, and radius. m is the mass of the impactor, b is the impact parameter, and v_∞ is the relative velocity of the stars before the encounter. Although a massive star spends only a small part of its life as a RSG, this is the only phase in which it has a non-negligible probability of capturing a companion because R^2 is very much smaller in the longer main-sequence phase. f is a "reduction factor" (FPR) to account for incomplete coupling between the collision frequency and the $l = 2$ mode of the RSG. FPR give limiting forms for f of $k\left(\frac{M}{m+M}\right)^{1/2}\left(\frac{b}{R}\right)^{3/2}$ for collisions in which this term is $\ll 1$ and the inverse exponential of this when it is $\gg 1$. We conservatively enforce continuity by switching to the latter form when $f = \exp(-f) \approx 0.567$. k is a constant in the range 2 to 3 which relates the fundamental frequencies of the RSG to its mass and radius.

The collision cross-section, $\sigma(v_r)$ in Equation 6.4 includes a term for gravitational focussing:

$$\sigma_{gf} = \pi b^2 \left[1 + \frac{2G(M_1 + m)}{v_r^2 b}\right]. \tag{6.6}$$

When the particles can be treated as point masses, M_1 is the mass of the primary. Obviously, for a penetrating encounter M_1 is reduced.

The relative velocity distribution, $f(v_r)$, can be related to the observable systemic velocity dispersion, σ_v, with some reasonable assumptions. For example, if both the RSG and impactor populations of stars have Maxwellian velocity distributions with the same one-dimensional dispersion, σ_v, then $f(v_r)$ is a Maxwellian with dispersion $\sqrt{2}\sigma_v$ (Binney & Tremaine 1987, p. 485). In this case, the integration over v_r yields

$$\tau \sim 4 \times 10^6 \left(\frac{n_*}{10^7\,\mathrm{pc}^{-3}} \right)^{-1} \mathrm{yr}. \tag{6.7}$$

As a massive star spends $\sim 1\,\mathrm{Myr}$ in a very distended state (cf. Schaller *et al.* 1992), these calculations indicate that roughly one out of four of the RSGs in the GC will capture a companion. This is in the target regime mentioned in Section 6.5 which can explain the enhanced He I star population without making the presence in the region of RSGs such as IRS 7 problematic. Although the approximations used to derive this collision rate are intended for close passes rather than penetrating encounters and for a mass ratio closer to unity, this calculation is sufficient to show that an enhanced binary-capture rate is worth further examination.

6.7.7 Tidal-Capture Rate — Numerical Estimates

Three pieces of further research suggest that FPR's formulation of the reduction parameter, f, is accurate only for grazing encounters and that second-order effects dominate over the frequency coupling inefficiency when the stars collide. Detailed smooth-particle-hydrodynamics (SPH) simulations of parabolic encounters applicable to globular clusters (Davies *et al.* 1991) are in very close agreement with Equation 6.5 for near-grazing encounters but show that the reduction factor should remain closer to unity for more distant encounters (see Figure 6.1). Simulations by the same group show that the efficiency is over-estimated for encounters which penetrate within $b/R_{RG} \approx 0.7$. Two detailed piecewise-parabolic-method (PPM) hydrodynamic simulations conducted for this project by Dr. Ruffert similarly suggest that the energy loss saturates near the value predicted for grazing encounters.

Most of the collisions of interest for this analysis occur at a large fraction of the stellar radius where the cross-section is large but the energy transfer is still adequate

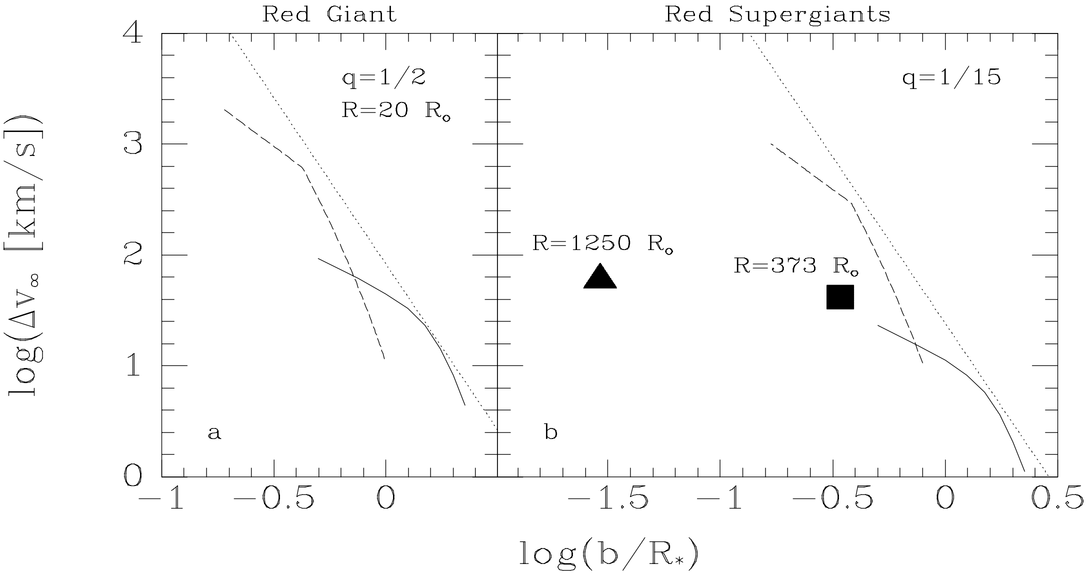

Figure 6.1: Comparison of Tidal Energy Loss Estimates.
a: The analytic approximation of FPR (dashed line) is compared with detailed hydrodynamical models (Davies *et al.* 1991, solid line). The simulations involved a $0.8\,M_\odot$, $20\,R_\odot$ red giant as a target and had a mass ratio, q, of 1/2. The dotted line is the FPR formulation with the reduction factor, f, set to unity. The excellent agreement with the latter at $\log x = 0.2$ shows that f should be nearly 1 for close, non-penetrating encounters, but the efficiency falls off even more steeply for collisions than estimated by FPR.
b: In this panel, the FPR approximation (dashed and dotted lines as above) is compared to Ruffert's hydrodynamical simulations (points). The Davies simulations have been shifted for $q = 1/15$ for comparison. In these plunging collisions, the energy loss is significantly over-estimated by FPR's formulae, even with f reflecting the frequency coupling inefficiency. However, the shifted Davies simulations would agree very well with the Ruffert points if extended, indicating a saturated dependence on impact parameter.

to result in a bound binary. An assessment of $v_{crit}(b)$ could be determined by simulating a large number of collisions with the same techniques used by Dr. Ruffert. However, a much simpler analysis of the dominant physical effect in this transition region suffices. Outside the star, the tidal distortion is geometrically simple but the collision timescale is too slow to excite the dominant oscillation mode; this is the factor FPR's f addresses. In plunging collisions, a detailed simulation is required to model the complex distortion. In between, an improved consideration of the tidal distortion geometry reveals the saturation of v_{crit}. Equation 6.4 with f set to 1 is simply the maximal tidal distortion energy at periastron. This can be extended numerically into the regime of collisions. To conduct this analysis, the model RSG is considered in a Cartesian grid and the tidal field introduced by the perturber at an arbitrary point and the resulting tidal distortions are computed for each bin and propagated to neighboring bins. The distortion is a compression or expansion in the direction to the perturber such that hydrodynamic stability is restored, $\nabla\vec{P} = \vec{F_o} + \vec{F_{pert}}$. The biggest potential flaw in this analysis is that it ignores the time dependence of the problem and assumes that maximal tidal distortion will occur, the factors which the FPR f is intended to address. However, there is good reason to believe that this is a good approximation because the distortion is no longer harmonic and the collision timescale is shorter than the thermal timescale; hence, the collision acts as a geometrical perturbation to the stellar structure. Consider by analogy a rubber ball which is bounced on a firm surface: the ball distorts geometrically ($ds \rightarrow ds'$) until the pressure gradient is sufficient to halt further compression rather than absorbing the energy of the impact through a thermal ($\vec{P}$) adjustment. The results of this analysis, presented in Figure 6.2, confirm that the reduced energy transfers in the Davies *et al.* (1991) and Ruffert collisions result from this more complicated distortion geometry.

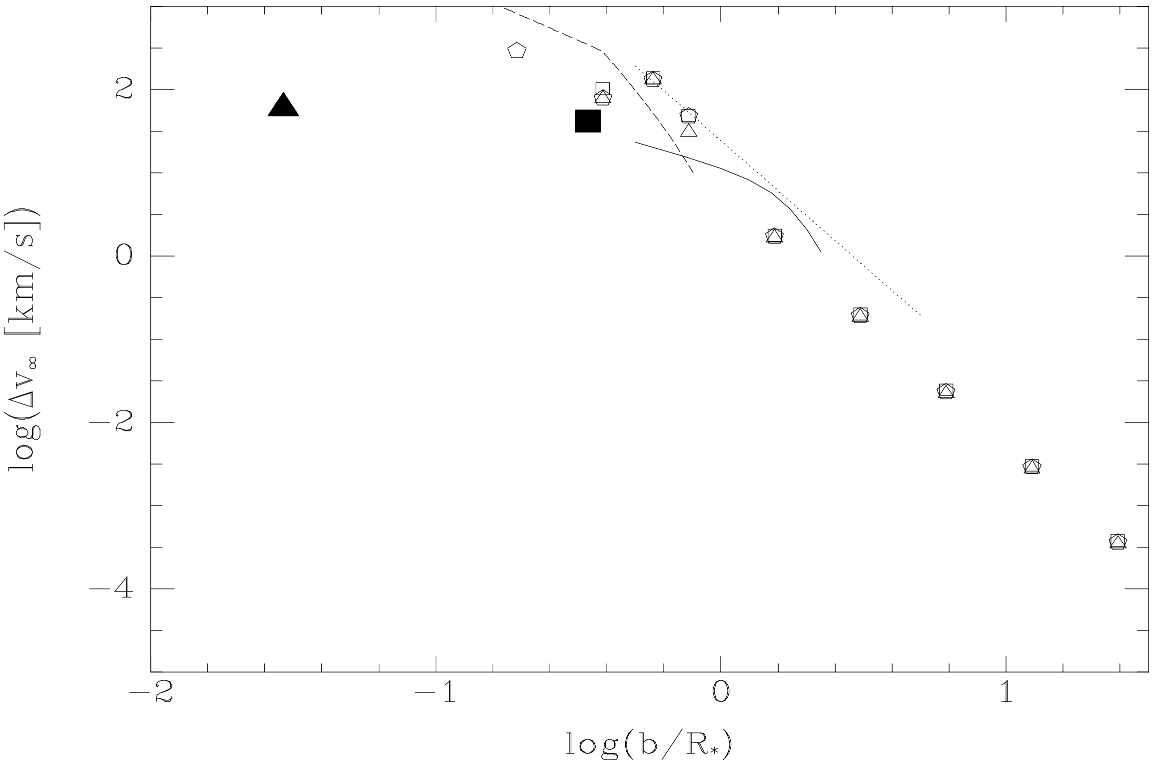

Figure 6.2: Estimated Tidal Energy Loss in Collisions. The second-order tidal estimates approximately connect the regime of close passes where the FPR approximation is valid with the highly damped, plunging encounters sampled by the hydrodynamic simulations of Ruffert. These calculations are based on a $1\,M_\odot$ impactor and a Woosley model RSG. The various open symbols illustrate the numerical stability of the code to different rejection criteria required by the coarse and unphysical binning of the target star. The filled symbols and lines are as in Figure 6.1*b*.

These disparate but consistent simulations were the basis for a three segment power-law fit to the capture cross-section:

$$\log \Delta v_\infty = \begin{cases} -0.15 \log b/R_* + 1.548 & \log b/R_* < -0.5689 \\ -1.006 \log b/R_* + 1.061 & -0.5689 \leq \log b/R_* \leq 0.197. \\ -5.294 \log b/R_* + 1.9065 & \log b/R_* > 0.197 \end{cases} \qquad (6.8)$$

Integration with this cross-section predicts a capture timescale of

$$\tau = 42 \left(\frac{n_*}{10^8\,\mathrm{pc}^{-3}}\right)^{-1} \left(\frac{m}{1\,\mathrm{M}_\odot}\right)^{-1.1} \left(\frac{\sigma_v}{140\,\mathrm{km/s}}\right)^{3} \mathrm{Myr} \qquad (6.9)$$

with weak dependences on M and R (taken to be $15\,\mathrm{M}_\odot$ and $400\,\mathrm{R}_\odot$). The indicated dependence on σ_v is only a first order estimate and would not apply for substantially different dynamical systems. This interval is much longer than the expected lifetime of a RSG. Hence, tidal capture of low-mass stars or remnants is unlikely to influence the evolution of massive stars in this region. As we have also seen that core ejection is inefficient in this system, it appears that any mechanism involving collisions with the background population (such as mergers or core exchange) will not explain the observed population. Tidal capture by lower-mass stars, which would have mass ratios closer to unity and longer life spans, may well be important, but is not expected to produce such luminous products. Gravitational settling and stellar mergers will enhance the fraction of higher-mass objects in the central regions (cf. Morris 1993; Lee 1987), and interactions with these more massive objects are individually more likely to result in capture. But such objects must be less numerous to remain consistent with the observed mass limits, and it is very unlikely that such massive objects even dominate the central mass. Hence the specific form of the mass-dominating population does not influence this result.

6.7.8 Tight Binaries — Survival

Especially because the relevant encounters are physical collisions, any binaries which are formed this way will be tight (as is always the case for tidal-capture binaries, Lee & Ostriker 1986). If a common-envelope phase does not commence at once, it will do so shortly due to continuing tidal influences and the further evolution-driven expansion of the primary. There is a small probability that the binary system will interact with a third star (see the review by Hut 1985). As the pre-contact binary is "soft" in terms of the cluster dynamics, it would be more likely to lose binding energy in such an interaction ("Heggie's Law"). The equilibrium dissociation (evaporation) timescale in the region for these binaries (Binney & Tremaine 1987, p. 536) is

$$t_{evap} \approx 2 \times 10^{7} \left(\frac{\rho_c}{10^{8}\,\mathrm{M_{\odot}pc^{-3}}}\right)^{-1} \left(\frac{a}{400\,\mathrm{R_{\odot}}}\right)^{-1} \left(\ln \frac{a}{400\,\mathrm{R_{\odot}}} + 2.5\right)^{-1} \mathrm{yr}. \tag{6.10}$$

Although this timescale is of importance to loose, coeval, massive-star binaries, it is slower than the progression from tidal capture to common-envelope evolution.

6.7.9 Common-Envelope Evolution — Observable Signatures

If the He I stars have experienced a common-envelope phase they may be spectroscopic binaries ($K_1 \sim 5 \sin i\,\mathrm{km\ s^{-1}}$, $K_2 \sim 100 \sin i\,\mathrm{km\ s^{-1}}$) or they may be rapidly rotating as a consequence of coalescence. Hjellming & Taam (1991) show that if the secondary emerges from the common-envelope phase before coalesence, the effects on the secondary will be minimal; the only peculiarity a post-common-envelope secondary would show would be a very short ($\lesssim 120\,$day) period. If the final state is a merger, the orbital angular momentum at the time when the intruder touches the core is quite high, $L \gtrsim (Ga/(m+M_c))^{1/2} m M_c$; the separation a would be expected to be $\sim 10^{11}\,$cm. In one extreme, if the resultant merger product remains as centrally condensed as the RSG core, the induced rotational velocity could be as high as $2000\,\mathrm{km\ s^{-1}}$. Despite this, the change in rotational velocity may not be detectable. Another limit is given by a uniform ball with the maximum size deduced for an IRS 16 component from $m_K = 8.8$ and $T_{\mathrm{eff}} \gtrsim 15,000\,\mathrm{K}$ of $170\,\mathrm{R_{\odot}}$, which would have an induced rotation of only a few km s^{-1}. Also, the photosphere might rotate significantly more slowly than the central mass condensation. However, detection of anomously fast rotational velocity in an IRS 16 component would be strong support for the envelope ejection model discussed here.

6.8 High-Mass Binaries

Even in the field, the fraction of high-mass stars in binaries is high, at least 30% (see the review by Abt 1983) and possibly much higher. Smaller and more biased samples (Garmany & Conti 1980) indicate that among these binaries, mass ratios near unity and very short periods (days) are favored. A survey (Mantegazzen *et al.* 1980) finds orbital separations $a \sim 1.5(R_1 + R_2)$, where R_1 and R_2 are the stellar radii. In such tight binaries, stellar evolution can be dramatically influenced by mass transfer and mass loss (e.g., Podsiadlowski *et al.* 1992). This and other studies prompted by the unexpectedly blue progenitor of SN 1987A have used modified stellar evolutionary calculations which account for rapid mass transfer such as occurs with Roche Lobe overflow. Podsiadlowski *et al.* (1992) expect this to enhance to 30 – 40% of massive stars the fraction appearing as "helium stars", a group which are clearly analogous to the GC stars. Further, there is observational evidence of systems which are currently undergoing mass transfer (e.g., AZ Cas, Podsiadlowski *et al.* 1992) or obviously have done so.

The fraction of massive stars in binaries tight enough for significant interaction might be further influenced by unusual formation processes in the GC or by binary hardening in interactions with field stars. In manners yet to be identified, star formation conditions in this region may lead to an enhanced fraction of high-mass stars in tight binaries with other early-type stars. There is some observational support for this hypothesis. Although giant H II regions generally do not have strong central concentrations, the massive star formation regions 30 Dor and NGC 3603 each have compact cores (R136 and HD 97950, respectively) composed of numerous massive stars (Moffat *et al.* 1985; Moffat *et al.* 1994; Drissen 1994) which should be compared to the GC central cluster. Several properties of these clusters are noteworthy. First, both have very high central stellar densities; estimates are seeing limited (even with $WFPC$!) but of order 10^5 – $10^7\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$, although they are not expected to have coincident concentrations of low-mass stars. Second, both have WNL stars in very tight binaries. Moffat *et al.* (1985) also note a pronounced concentration (steeper than the light concentration) of WRs in HD 97950 which they argue results from gravitational settling of the more massive WR progenitors. This work provides an alternate explanation: in the much denser core of NGC 3603, which is thought to be approaching core collapse, binary formation and common-envelope evolution may explain the enhanced WR frequency. Further, recent data (Drissen *et al.* 1995) find that the WRs in HD 97950 have 6 coeval O3V–III neighbors. As WRs are commonly thought to evolve *from* the most massive O stars, which in this coeval cluster are seen relatively unevolved, this can be interpreted to implicate a second influence (Hanson, private communication). We suggest this influence may be binary enhancement.

Even if the binary fraction or period distribution is not peculiar, frequent ($\tau \sim 10^5\,\mathrm{yr}$) interactions of the expected fraction of high-mass binaries with the mass-dominating population will on average drive the high-mass binaries tighter. This would drive some binaries which would be wide enough to avoid mass exchange if they were in the field into a common-envelope phase. Unlike the high–low-mass binaries discussed in Section 6.7.5, the binding energy of high-mass binaries will exceed the cluster's characteristic dyanamical energy, $m\sigma_v^2$, and hence will on average be driven tighter in binary–field star interactions. Although the binding energy changes slowly, it increases over the whole lifetime of the binary. Survival of hard binaries is very likely: they can not be gradually "evaporated" like soft binaries because most collisions will instead make them harder. Instead, it requires an atypical collision with an unusually high velocity star to drive the binary over the Heggie's Law watershed in one event. Hence, the high-mass binaries formed in the GC either through normal or biased star formation will be driven towards Roche Lobe exchange. However, the importance of these interactions should not be over-emphasized: most have a small influence on the binding energy. The timescale over which the binding energy changes by a characteristic energy $m\sigma_v^2$ (cf. Binney & Tremaine 1987, p. 539) is comparable to a massive star's lifetime (10^7 yr). Also, these estimates are coarse because the system will likely behave as a 3-body system for an interval which is significant compared to the time between interactions.

Although Roche Lobe overflow is likely the dominant process in these binaries given the tendency for binary hardening, it is still instructive to review other important processes in high-mass binaries. Several of the interactions between massive stars dismissed in Section 6.5 need to be reconsidered in this context because typical binary separations are much smaller than the separations between the known He I stars. Identifying the GC He I stars as binaries would also help (although only slightly) explain the extraordinary luminosities of the brightest sources. However, the He I source probably still dominates the near-IR of such a binary regardless of whether the companion is blue or red. Specifically, if the companion is a blue, main-sequence late-O star, it would be several magnitudes fainter in the NIR than the cooler primary. On the other hand, a red companion's contribution must be small because these sources have Rayleigh-Jeans spectra. Intermediate-temperature companions could contribute up to approximately equal flux without making the emission equivalent widths too problematic, but are strongly dis-favored by evolutionary expectations. Most interesting in this context and most probable are binaries with companions of nearly equal mass which have either gone supernova during the RSG phase of the current He I star, or are late-O main-sequence stars.

At first assessment, it seems that if RSGs are in massive star binaries a significant fraction of the time, this could explain all of the observed blue stars by supernova stripping (Livine *et al.* 1992). However, the odds that each of the observed WR or "transition" objects were stripped during their RSG phases by a companion's SN are much smaller because the ratio of RSG to total lifetime for a massive star is $\sim 10\%$. Hence, the coeval binaries would need to have components with nearly equal masses.

In contrast, the potential, less massive, unseen O star companions would have continual winds and high UV fluxes. No coincidental timing is required for these influences to operate when the primary is extended. Hence, the possibility that the He I stars have been individually stripped by binary companions cannot be ignored. Using the same mass-loss characteristics as in Section 6.5 but a binary separation of $2000\,\mathrm{R}_\odot$, the wind kinetic energy intercepted by the RSG would be enough to liberate substantial material, $\lesssim 10^{-3}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, if the conversion is efficient. The luminosity power is again about 100 times as much, but the conversion is probably substantially less efficient. Further, at such tight orbital separations, the RSG will overflow its Roche Lobe if the companion is also massive. Regardless of which influence dominates, it is clear that an O-star companion would have a substantial effect on the evolution of a RSG (cf. Podsiadlowski *et al.* 1992). Indeed, such binaries remain a viable explanation for field WR stars.

Considering that the binary fraction of OB and WR stars is generally subject to controversy, it seems ambitious to try to detect binaries among the luminous stars in this region which is relatively difficult to observe. However, adaptive optics and space based NIR observations make it feasible to conduct meaningful searches for eclipses among the prominent members. The narrow emission lines also make a spectroscopic search plausible, but care must be taken to avoid confusion from crowding or intrinsic wind variations.

6.9 Application to Lower-Mass Red Giants

There has been considerable research on the influence of the GC environment on Red Giants (RGs) prompted by two observational clues. The first is the CO depletion region described in Chapter 4; an image can be found in Haller *et al.* (1996). The second is a series of mid-IR emission sources which were interpreted as stellar-mass clouds (Lacy *et al.* 1982) created by stellar collisions. Although these mid-IR sources are now thought to be part of a coherent structure (Lacy *et al.* 1991), the CO depletion region remains an important piece of the GC puzzle with uncertain explanation. Hence, it may be valuable to review how some of the mechanisms considered in this chapter apply to lower-mass RGs in the nucleus of our own and other galaxies.

In many respects, predictions for RGs are expected to be much more secure: our understanding of their evolutionary timescales and structure are much better than for RSGs, their lifetimes exceed the equilibrium timescales for GC dynamics, and these mechanisms have been directly modeled with RGs in the context of globular cluster core collapse. The important distinctions of this region from globular cluster cores for RGs are the much higher relative velocities and (presumably) stellar densities. The most important distinction from RSGs other than lifetime is in RG opacities and structure: a red giant of solar metallicity which loses partial envelope mass will rebound and appear as a lower-luminosity red giant. Although in detail the energy source is different, “red clump” stars are an adequate demonstration of this: after losing mass ascending the red-giant branch and the helium flash, moderate-metallicity low-mass stars populate the reddest part of what would be the horizontal branch in lower-metallicity populations, where it intersects the red-giant branch. Nearly complete envelope loss would break the opacity dependence that drives runaway expansion (Renzini *et al.* 1992) and leave a bluer object without CO absorption features. A central concentration of such objects would dilute the CO feature in a manner consistent with the observations. However, they would not have the WR-like characteristics which make the GC He I stars individually identifiable.

We briefly remind the reader that several models for unusual stellar development in the GC have been developed without resorting to recent star formation, and they have been thoroughly discussed by their originators and following papers. For example, the prediction of ongoing stellar mergers (cf. Lee 1993) certainly must apply to some extent. However, it is not expected to have any impact on the two observational traits discussed above because the merger process is expected to be almost completely efficient, yielding only a more massive star. Similarly, the model in which black holes aquire envelopes from collisions with red giants (Morris 1993) likely influences the GC region but is not relevant to these problems.

The CO layer in RGs in the vicinity of a strong UV source could be externally dissociated. If the He I stars, which may dominate the region's UV, are responsible, one would expect a stronger correlation between these stars' locations and the observed depletion region. For example, AHH-NW and IRS 15 are likely stronger UV sources than the AF star, but located outside the observed depletion region. External ionization from Sgr A* looks feasible given the spatial distribution, but the finding that stars dominate the UV makes this unlikely. Although a low-luminosity, harder-UV source at Sgr A* is consistent with the observations, it should be the softer, stellar UV which dominates the CO dissociation. The unseen main-sequence

O stars are a more promising source of external ionizing radiation. These stars may dominate the region's UV and are likely to be somewhat concentrated to the depletion region by gravitational settling.

Core ejection was first considered (Tuchman 1985) specifically to explain the GC mid-IR clouds, and would also account for a concentration of continuum sources in the densest regions which would dilute the CO absorption. In the original analysis, it was assumed that white dwarfs would be abundant and serve as the perturbing projectiles. We can consider as a limit that most of the central mass density is in the form of $0.8\,\mathrm{M}_\odot$ white dwarfs and that the target RGs remain confined to this region throughout their RG phase. A more realistic model would consider stellar evolution and gravitational settling to estimate the white dwarf space density and realistic stellar orbits with a fraction of the RG phase in the densest regions. Equation 6.2 still applies, but the energy binding the envelope to the core is substantially lower. Accepting Tuchman 1985's "typical" RG parameters ($M = 2\,\mathrm{M}_\odot$, $M_c = 0.62\,\mathrm{M}_\odot$, $L = 6000\,\mathrm{L}_\odot$, $\rho_{env} \propto r^{-\alpha}$ with $1 \leq \alpha \leq 1.5$), $BE \approx 1.5 \times 10^{46}\,$ergs, yielding a $b_{crit} \approx 50\,\mathrm{R}_\odot$. However, his $R \approx 580\,\mathrm{R}_\odot$ (estimated from his Figure 2; implies $T_{\mathrm{eff}} \approx 2100\,\mathrm{K}$) RG is probably generous. A review of RG evolutionary tracks (e.g., Sweigart *et al.* 1989) suggests that a $50\,\mathrm{R}_\odot$ star is more appropriate. Such a star, assuming the same envelope density profile, has about 10 times as much binding energy, requiring a collision 3 times as close. A coarse estimate of the interval between such encounters for a RG is

$$\tau \sim 6 \times 10^7 \left(\frac{n_*}{10^8\,\mathrm{pc}^{-3}}\right)^{-1} \left(\frac{\sigma_v}{140\,\mathrm{km/s}}\right)^{\alpha} \mathrm{yr}. \tag{6.11}$$

Obviously, an integration considering the evolving envelope size and profile would improve this estimate, but since this must compete with the fast evolution in this upper portion of the RG branch, it is sufficient to show that this process does not have a significant influence on the population of low-mass stars. This result also applies to intermediate-mass stars: although they are substantially more luminous and larger, the increased core mass compensates for the more extended envelope. The core–envelope binding energy is comparable and a similarly hard (and rare) kick is required to free the core. Hence, although core ejection is expected to occur often enough to contribute to creation of stellar-mass gas clouds, it is not expected to alter integrated properties such as the CO absorption depth significantly.

Although lower-mass stars also inflate to large cross-sections, the ratio of main-sequence to RG lifetimes beats the increased cross-section. Further, in this dynamically hot system, RGs capture only a small fraction of objects with which they collide, but more compact main-sequence stars can dump more than $200\,\mathrm{km\ s^{-1}}$ in relative velocity in a grazing encounter and hence most collisions result in capture. If white dwarfs dominate the central mass density and $n_* \approx 10^8\,\mathrm{pc^{-3}}$, a main-sequence star will collide with a white dwarf every $\sim 2\,\mathrm{Gyr}$. Hence, a large fraction of the Population II component should have captured companions. These companions would typically have orbits of only a few $\mathrm{R_\odot}$ and hence be engulfed in a common envelope during the giant phase of the primary. There are some data on field RGs which demonstrate that such tight binaries prevent evolution through the RG phase. Unlike samples of warmer stars, there are indications of a deficit of RGs in binaries with periods less than $\sim 1\,\mathrm{yr}$ (Griffin 1985; Duquennoy & Mayor 1991). If correct, this suggests that the shorter period systems undergo mass transfer or common-envelope evolution, preventing the primary from ever appearing as a RG.

Models considering realistic stellar orbits, binary dissociation rates, and a star formation history over the age of the Galaxy could be combined with improved constraints on the composition of the central mass excess to assess the significance of tidal capture to the central red-giant population. Three factors may reduce the fraction of low-mass stars with captured companions from unity: the fraction of the central mass density in the form of stellar remnants may be significantly smaller than assumed here, some of the intermediate- and low-mass stars may be younger than the Galaxy, and most of their orbits could be spent in lower density regions.

It is now possible to test the mechanism of tidal capture with RGs in globular clusters with HST observations of core populations. For example, M15 has a deficiency of RGs in the central $6''$ which explains the bluer core observable from the ground (Guhathakurta 1995). A bluer core is seen in many post-core-collapse clusters but not in less concentrated cluster cores. Hence, these data support tidal capture during core collapse. Further work on the statistics and distribution of RGs and blue stragglers in globular clusters will further constrain the capture efficiency.

As briefly reviewed in Section 4.1, the characteristics and cause of the CO depletion region are still poorly understood. It remains unclear whether a deficit of RGs exists, much less what fraction of expected RGs are absent, as the presence of a second, bluer population is a viable explanation for the entire effect. Nonetheless, capture of companions may provide a significant reduction in the central density of RGs, as well as explain the gas clouds. If the clouds are formed in this manner (they may instead be part of a coherent structure), they should have detectable expansion velocities and distorted morphologies like elliptical or butterfly planetary nebulae (Livio & Soker 1988).

6.10 Summary

Many models for the alteration of stellar evolution in the GC region have been reviewed and most have been found to operate too slowly to explain the collection of blue massive stars. We confirm what could be surmised from the extraordinary luminosities of several of the IRS 16 sources (see Figure 5.3), that single star evolution cannot be expected to produce this population. We can identify no sufficiently strong interaction mechanism among the massive stars to modify their evolution, such as wind or supernova explosions. It also appears unlikely that outbursts by Sgr A* can account for the population. New numerical results indicate the same for tidal capture of low-mass stars or remnants by RSGs and for core ejection in collisions.

It therefore appears likely that the peculiarities of the observed population are a result of their conditions of formation. For example, tight, coeval binaries are a possible cause for anomalous evolution of massive stars. High-mass binaries are common in all environments and there is some evidence (in the dense cores of 30 Dor and NGC 3603) that tight binaries are more likely in dense star forming regions. Cluster evolution will also slowly drive high-mass binaries harder. Transfer to the secondary or expulsion from the binary of the primary's envelope is expected to leave a helium star consistent with the observed properties of the GC stars, although the luminosities of the brighter members remain problematic. Through binary evolution, the mass range from which WR-like stars can be drawn and the duration of this phase would be increased. According to this interpretation, the distinction of the GC from the nuclei of M31 and M32 is that the latter have not had recent episodes of massive star formation. Although difficult, a search for binaries among the He I stars could confirm these conclusions. Very high resolution observations of additional dense regions with recent star formation would also test this conclusion.

A second possibility is that unusual conditions of formation led to a distribution of stellar masses which is significantly different from that expected from a standard IMF. If so, then this concentration of stars which are analogous to the most extreme stars seen in other environments could arise from normal evolution of an abnormally high number of very massive and very luminous stars. This cluster may unexpectedly prove useful for studies of massive stellar evolution.

Tidal capture by lower-mass main-sequence stars is expected on an interesting timescale and can explain the observed gas clouds. The clouds should have observable signatures if they are expelled common envelopes. This process may also operate at a sufficient rate to reduce the spatial density of RGs measurably in the central 1/2 pc by accelerating their evolution to white dwarfs. A quantitative estimate of the effect will require more detailed analysis than is provided here. Such an analysis is of interest because this process could explain the decrease in CO absorption depth that is observed in the region.