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The Effect of Tidal Disruptions on Giant Stars in the Galactic Center

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ABSTRACT

Recent observational data suggests the depletion of late-type giant stars in the inner most region of the Galactic Nucleus (Buchholz et al. 2009; Do et al. 2010). Using dynamically evolving Fokker-Planck models of the Galactic Nucleus, we have followed in detail the stellar distribution as it evolves through the post-main-sequence phases. Of particular interest was the effect of stellar collisions and tidal disruptions by the central massive black hole on post main sequence stars as they expand in size. By modeling tidal disruptions and stellar collisions, we have found that there should be a significant depletion of the giant stars in the innermost regions of the nucleus. Our models also suggest that tidal disruptions were found to have a larger effect on the depletion of giant stars than stellar collisions in this region.

1. Introduction

A galaxy is a gravitationally bound aggregate of stars, on the order of 100 billion in count. Galaxies can be categorized based upon their structure: spiral, elliptical, and irregular. Our own Galaxy is called the Milky Way and is a spiral galaxy. The structures of spiral galaxies can be further organized into several substructures. The galactic halo is a spheroidal distribution of stars extending to the outermost regions of the galaxy. The galactic plane is a disk usually containing the majority of the galaxys stellar population, gas, and dust, which forms the spiral arms of the galaxy. An inner spheroidal distribution, known as the galactic bulge, extends a few thousand light-years from the center. The very innermost region of the galaxy is called the galactic nucleus. Our Galactic Nucleus is only about 8 kiloparsecs away, making it one hundred times closer than the next nearest nucleus (Ghez et al. 2008). Therefore, the Galactic Nucleus provides a unique opportunity to observe and analyze the characteristics of the very centers of galaxies.

In the Galactic Nucleus number of stars per cubic parsec is nearly a trillion times greater than in the solar neighborhood, exceeding $10^7 M_{\odot} pc^{-3}$ in the centermost arcsecond (Genzel et al. 2003). In these dense conditions, interesting phenomena can occur that give insight into the formations of galaxies. It has not been until the last decade that there has been enough data to compare computational models to our nucleus. The dust residing between observers on Earth and the Galactic Nucleus has a strong effect on light passing through; visible light is extinguished. Therefore, the Galactic Nucleus was largely unobserved until recently. The dust does not have as great extinction in the infrared and near-infrared. This allows observers to see stars in the center of the Galaxy, albeit only intrinsically red stars and very bright stars with a strong red component. Observations have seen the existence of red giant stars and young, massive stars (Ghez et al. 2003).

Continued observations have shown that many galaxies, including our own Milky Way, harbor super massive black holes at their centers (Lynden-Bell & Rees 1971). These supermassive black hole can be anywhere for 1 million to several billion times the mass of the Sun. The supermassive black hole at the center of the Milky Way, known as Sgr A*, has been measured to be over $4 \times 10^6 M_{\odot}$ (Ghez et al. 2008).

When the Milky Way first formed there was likely no central black hole. Shortly after the first generation of stars in the Milky Way, black holes of roughly 50-100 solar masses, created from massive stars, are believed to gravitationally segregate to the galactic center due to dynamical friction. As these relatively low-mass black holes orbited about each other, they are thought to have emitted gravitational waves in accordance to the general theory of relativity, depleting their orbital energy until they collapsed toward each other and formed a more massive seed black hole. Once formed, this seed black hole would gravitationally draw stars and clouds of gas closer to it, accreting the mass and growing in size (Shapiro & Teukolsky 1985). The black hole is believed to be able to gain this mass from the surrounding system through three mechanisms (Murphy et al. 1991; Freitag & Benz 2001). By understanding the roles these mechanisms play in redistributing the mass in the Galactic Nucleus, one can further understand how the system evolves.

One mechanism through which central black hole can grow is by the consumption of gas ejected by stars as they evolve from main sequence stars into red giants. The main sequence stage of a star is its most stable, accounting for 90 to 95% of its lifetime. The main sequence stars fuse hydrogen into helium only in their cores. The sun is an example of a main sequence star. When a main sequence star exhausts the hydrogen in its core, the core contracts and ignites a hydrogen fusing shell surrounding the remaining helium core. This causes the stars to swell becoming a luminous red giant star. Red giants swell to tens to even a hundred of times in diameter to our Sun. Eventually, the helium core can begin to fuse into higher elements. This causes the star to reduce its luminosity and radius. The star then burns through its core of helium significantly faster than the hydrogen core. The shell around the core begins to fuse and the star ascends the Asymptotic Giant Branch (AGB) to become a supergiant, mirroring its transformation into a giant but to a greater extent. The radius of an AGB star is much larger than that of even the giant star, ranging from several hundred to on the order of a thousand times the radius of the Sun. A massive star may be able to ascend additional AGBs as it fuses through its core of heavier elements. Beginning with the red giant phase, the star will eject mass from its outer layers. A typical star will lose between 50 and 90% of its mass during this stage. Some of this ejected mass will be accreted by the central black hole. What remains after the AGB phase is a compact object: a white dwarf, a neutron star, or a stellar black hole.

Another mechanism, tidal disruption, occurs when a star passes too close to the central black hole. Extreme tidal forces overcome the stars internal forces and rip the star apart, causing the stars mass to spiral into the black hole. The radius from the central black hole at which a star is tidally disrupted, known as the Roche limit, follows the equation

$$R_{Roche} = \left(2\frac{M_{BH}}{m_*}\right)^{1/3} \times R_* \qquad (1)$$

where R_{Roche} is the Roche limit, M_{BH} is the mass of the central black hole, m_* is the mass of the star, and R_* is the radius of the star. Inside of this radius from the center, the star of corresponding radius and mass would be destroyed. This region is known as the loss cone. The third mechanism for feeding the central black hole is via mass ejected by stellar collisions. The rate of stellar collisions is a given by

$$\Gamma_{coll} = n(r) \times v_{rel} \times \sigma_g \qquad (2)$$

where $n(r)$ is the number density of the stars, v_{rel} is the relative velocity between the impacting stars, and

$$\sigma_g = \pi R_{min}^2 \left(1 + \frac{2G(M_1 + M_2)}{R_{min}v^2}\right) \qquad (3)$$

is the gravitational lensed cross section of collision, with R_{min} as the minimum distance between the two stars needed to collide and M_1 and M_2 represent the masses of colliding stars. Recall that the stellar density at the nucleus is approximately 10 trillion times greater than that of solar neighborhood. The velocities of the stars near the galactic center are greatly increased due to the deep gravitational potential that results from the large mass of the Galactic Nucleus. Both these factors cause collisions to occur in the nucleus more often than elsewhere in the galaxy. Most stellar collisions are main sequence-main sequence because they are much more common due to their much longer lifetimes relative to giant and super giants. But since the cross section of a star is proportional to the square of its radius, red giants and supergiants will be much more likely to experience stellar collisions. Red giants, with their large cross section, may collide with a main sequence star which could result in the destruction of both stars. Some of the mass from the destroyed stars may be consumed by the central black hole.

Computational models of the Galactic Nucleus and lower massed systems like globular clusters have attempted to understand the evolution of these systems by incorporating the three mechanisms. Bahcall & Wolf (1976), in an early attempt, modeled a system of stars immediately around a black hole. Their results showed that when the system was dynamically relaxed, the density distribution around the black hole could be explained by a power law

$$\rho(r) \propto r^{-\gamma} \tag{4}$$

where ρ is the density, r is the distance from the center, and γ is the power relation, with a γ of 7/4. Murphy et al. (1991) further expanded upon this and demonstrated that γ takes on a value of 1/2 when collisions become dominant. The sphere of influence of the supermassive black hole extends approximately one arcsecond from the center of the Galactic Nucleus. Until recently, observations could not resolve this innermost region. With increased resolution, many, including Buchholz et al. (2009), Do et al. (2010), and Schödel et al. (2007), measured the number density of stars from the center of the Galactic Nucleus. The populations of giant stars were found to be dramatically depleted compared to the younger stars in the region. The explanation for this depletion would assist in the understanding of the evolution of the Galactic Nucleus.

This work contends that the depletion of late-type stars in the Galactic Nucleus can be explained primarily by the tidal disruption of stellar populations by the supermassive black hole as the stars evolve through their giant phases. Collisions will other stars and stellar remnants have a minimal effect on the distribution.

2. Methods

In modeling systems, there are numerous methods to apply. Each has its own advantages and disadvantages. For modeling a cluster of stars, like the Galactic Nucleus, one can use direct or statistical methods. The N-body method is an example of a direct method for calculating the evolution of a system of stars. Through the N-body method, each star is followed and the forces on each are calculated. This system then steps forward a small amount and then recalculates. This process repeats to move each star forward and to evolve the system. The advantage of the N-body method is that it is highly accurate at locating the positions of stars given the proper initial conditions. The disadvantage is that this method is highly computational intensive and dependent on the errors of the initial parameters. The number of calculation grows at an enormous rate with each additional star in order to take into consideration the effect it has with all of the other stars. This feature can create difficulties for modeling very large systems, like the Galactic Nucleus. The N-body method can be sped up by making the program run in parallel and on a supercomputer. This reduces the calculation time at a greater monetary expense.

Statistical methods avoid this limitation by making calculations based on distributions instead of individual bodies. Instead of following each individual star as the system evolves, statistical methods evolves the system by allowing the distribution of stars to evolve with time. The two well known and effective statistical methods are Monte Carlo simulations and the Fokker-Planck method. The Monte Carlo simulations depend on repeatedly taking random samples in order to make calculations. The Fokker-Planck method utilizes a differential equation to describe the evolution of the distribution of stars in the cluster. This method is generally faster than the Monte Carlo.

The Fokker-Planck method was chosen for this model. The model is an improved version of Murphy et al. (1991). The Fokker-Planck equation that is used in this model is

$$\frac{\partial N_i(E)}{\partial t} = -\frac{\partial F_{E_i}}{\partial E} - N_i(E)\nu_{coll_i} - N_i(E)\nu_{lc_i} \tag{5}$$

where $N_i(E)$ is the energy-space number density of the ith mass group. The energy corresponds to the orbital energy of the stars about the central black hole. The quantities ν_{coll_i} and ν_{lc_i} represent the rates at which mass group i lose stars due to collisions and loss cone, respectively. F_{E_i} is the energy-space flux for the mass groups given by

$$F_{E_i} = \sum_j \left(-D_{EE_{ij}}\frac{\partial f_i}{\partial E} - D_{E_{ij}} f_i\right) \tag{6}$$

The function f_i represents the velocity-space ditribution. The quantities $D_{EE_{ij}}$ are the elements of the diffusion tensor, which facilitate the diffusion of stars in the system into other energy levels. The values of $D_{E_{ij}}$ are the elements of the drift vector, which accounts for the drift of the distribution of stars.

The Fokker-Planck equation facilitates the dynamical evolution of the distribution of stars in the Galactic Nucleus (Figure 1). As the system evolves, the stars are allowed to drift due to stellar interactions. This can result in a mass segregation, where more massive stars gravitate toward the center. The accretion by the supermassive black hole and the effects of stellar evolution, stellar collisions, and tidal disruptions add further complications to the distribution.

To facilitate computational calculations, the range of energies the stars can have is divided into 100 discrete energy groups. It is assumed that the orbits of the stars are isotropic about the center of the galaxy. The orbits have no preference in their orientation, thereby allowing this system to be reduced to a one dimensional model. This isotropy also makes all of the eccentricity of the orbits equally likely. Therefore stars in a group share the same orbital energy but their orbits may range from circular to highly radial.

The spectrum of stellar masses is approximated by using 40 discrete mass groups of 0.1

to 50 $M_{\odot}$. The relative number of stars in each mass group is initialized by the Initial Mass Function. This function is described by three power laws covering low mass, medium mass, and high mass stars. A Kroupa mass function, favoring more low mass stars and fewer high mass stars, was used.

The metallicity, or the fraction of the stellar material that consists of higher elements, is also taken as an input for the model. This variable can have a dramatic effect on stellar evolution. This model was run with a metallicity of 0.01, a value slightly less than that of the Sun.

In order for the model to more accurately evolve the population of stars in the Galactic Nucleus, modifications needed to be made to the previous iteration of the program. The first modification was done by Phifer et al. (2009). This addition to the model allowed each mass group to evolve according to the mass and metallicity of the stars, based on the results of Pols et al. (1998). Before this change, all the stars in the model were assumed to be main sequence stars. The stellar radii in each mass group now changes realistically as the stars progress through their stellar evolution. The mass group that is in an evolved state around the age of the Galaxy in Figure 2 is shown to demonstrate how the radius of a star evolves. The radius stays fairly constant during the stars main-sequence phase, which lasts most of the stars life. The first peak shows the dramatic increase in stellar size as the star becomes a giant. The subsequent decrease in radius corresponds with the horizontal branch phase. With the second peak in radius, the star is in the AGB or supergiant phase. Following this phase, the star has lost most of its mass and becomes a compact white dwarf.

A further addition was needed for a greater inspection of the giant populations. Because the stars evolve relatively quickly through the giant phases, the steps forward in time had to be significantly reduced. The time step was adjusted to ensure that the model would not step over the change in the phase of a star. In addition, the model was slowed by a factor of 25 when a mass group was in the giant phase and by a factor of 100 during an AGB phase. For the example mass group, the model was slowed by an additional factor of 10 throughout the giant and AGB phases to increase resolution. It is believed that slowing the model down for these brief phases would not have any large scale effects on the outcome of the model, but would allow for a more accurate understanding of the mechanisms taking place. By allowing the mass groups to undergo stellar evolution in the model, the radii of the stars in the system change dramatically and thus have an effect on other mechanisms.

The latest model incorporates the addition of stellar evolution to more accurately take into account mass lost due to tidal disruptions and stellar collisions. Recall the equation for the Roche limit. The radius at which a star is tidally destroyed is proportional to the radius of the star. Because the orbits of the stars are assumed to be isotropic, stars with more eccentric orbits may have a part of their trajectories inside the new Roche limit, which grows with the evolution of the star. The model now takes into account the radius of each evolved stellar mass group when calculating the mass lost due to tidal disruptions. In addition, the rate of collisions is, as previously stated, proportional to the cross section of the stars. The rate of collisions is now calculated by individually comparing each mass group to each other. Stellar radii, relative population densities, and relative speeds of each mass group are considered. Because compact objects, including stellar black holes, have very small radii, they are able to penetrate straight through a larger giant. Since these compact objects have such high densities and giants have such low densities, the compact objects can strip mass away from the outer regions of the giants. To account for this, the mass lost from the envelope of the giant from a collision with a compact object found in Dale et al. (2009) was averaged.

In order to compare the model with observations, one mass group was examined. This mass group, with an initial mass of 0.95 $M_\odot$, was selected because its evolution into the giant phases begins past 12 billion years. This time scale is enough to allow stars that originated with the system to evolve into observable giants at the present day. It is not an exact concurrence, but the Galactic Nucleus has become largely dynamically relaxed by this time and thus the differences between the system at the time of the mass group's evolution and at the actual age are negligible.

3. Results

The addition of realistic stellar evolution, stellar collisions, and tidal disruptions to the model of the Galactic Nucleus increases its complexity and allows for a more thorough inspection of the mechanisms through which the system evolves.

As the system evolves, the distribution of the stars changes according to stellar interactions as well as the mechanisms through which mass is lost. In Figure 3, the density profile of the mass group, whose evolution coincides with the present age of the Galaxy, alters significantly as it evolves from a main-sequence star through its giant phases and into a white dwarf. Note the "hole" that develops in the inner most region as the mass group evolves; this is the loss cone. The tidal forces would destroy the stars within this distance from the supermassive black hole; therefore the model removes the distribution with orbits that cross into the Roche limit. The Roche limit for this mass group grows outward as the stars evolve into red giants, recedes as the stars decrease in radius along the horizontal branch, and reaches its extreme when the stars reach the top of the AGB phase. During the horizontal branch phase, the Roche limit is reduced and stars are able to diffuse back into lower orbits, thereby filling in some of the region that had been cleared of the mass group. Stellar collisions also play a role, as stars are destroyed in the densest region. Both mechanisms decrease in potency with greater distance from the center. Outwards from about 0.1 parsec the distribution of the stars remains largely unchanged. When the mass group reaches the final phase of its stellar evolution, its density for the inner most parsec becomes a power law with $\gamma = 7/4$. The compact objects have become too small to be destroyed by collisions or tidal disruptions, and therefore their population has become dynamically relaxed.

The effect each mechanism has on stars in the system is measured in the rate at which mass is lost by the stars. While the total mass loss rate is for the majority of the time dominated by mass ejected from stars throughout the course of stellar evolution, sudden spikes occur as the rates of tidal destruction and stellar collisions increase (Figure 4). Each dramatic increase in the mass loss rate corresponds to the inflation of the stars in a mass group undergoing the giant phases. The mass loss rate due to the loss cone stays largely above the rate due to collisions by nearly a factor of ten.

The rate of mass lost for the mass group increases as the distance from the supermassive black hole expands, up until a few parsecs where the rate drops off (Figure 5). As the stars in the mass group evolve and their radii increase, a sharp peak in the rate due to the loss cone takes form. From the end of the main-sequence to the conclusion of the red giant phase, the peak increases and moves outward. Stars in lower orbits around the black hole are tidally disrupted first and as the Roche limit for this mass group expands outward, stars further out are destroyed and none are left inside the limit to contribute to the mass loss rate. This results in the peak in the mass loss rate that moves outward. The rates return to a similar profile as in the main-sequence and then a comparable peak transition occurs again as the stars evolve up the AGB. The mass loss rate due to the stellar collisions increases as well as the stars' radii expands. Collisions begin to dominate the inner most hundredths of a parsec following behind the peak from the loss cone. While the increase in rate of mass lost by collisions is significant, it remains several orders of magnitude lower than the dramatic peak given by the loss cone. It is interesting to note that the two rates are not entirely independent of each other. The collisional mass loss rate seems to decrease in areas heavily dominated by the loss cone. When many stars are tidally disrupted in a region, there remain few that can collide with another object. As the mass loss rate increases, there becomes a depletion of the population that can reduce the rate of collisions.

The distribution of this mass group can be examined further with the removal of collisions and/or tidal disruptions. Collisions and tidal disruptions have an effect on both giants and main sequence stars but have virtually no effect on compact objects (Figure 6). The mass group in the giant phase shows the largest effect, whereas the differences for the main sequence stars occur largely interior to $10^{-}3pc$. Figure 7 shows the change in the density profile of just the mass group in its supergiant phase with the mechanisms selectively removed from the model. The density is the greatest when both mechanisms are turned off. Without the loss cone, the difference from the density with both mechanisms is significant. However, the profile without collisions follows closely to the profile with both. Since the density is altered to a greater degree by the inclusion of tidal disruptions as compared to the inclusion of stellar collisions, the model suggests that tidal disruptions play a more significant role than collisions in the distribution of stars as they evolve.

The model of the Galactic Nucleus demonstrates the dominating effect tidal disruptions have on the distribution of the evolved stars in the center most regions. As previously discussed, the loss cone causes a gap to form around the supermassive black hole for stars in the giant phases. Because the model simplified the system by reducing it to one dimension, the distances are radial and isotropic. The "hole" that developed because of tidal disruptions corresponds to the hollow center of a spherical distribution of stars. In order to compare the results of this model to observations, the spherical distributions needed to be projected into the plane of the sky. When projected into two dimensions, the depleted giant population appears as a flattened curve instead of a hole (Figure 8). This is in agreement with the results from Buchholz et al. (2009) and Do et al. (2010), suggesting a nearly flat profile for late-type stars.

4. Conclusion

With the addition of tidal disruptions and stellar collisions which vary with stellar evolution, this Fokker-Planck model has been able to more accurately discribe the processes occuring in the evolution of the Galactic Nucleus. The inclusion of stellar collisions which are realistically dependent on the stellar evolution was found to have little significance to the distribution of the system. This is in agreement with Dale et al. (2009), which found that collisions became less likely to occur outside of 0.1 parsec and there could not be the dominant mechanism to explain the depletion.The inclusion of the tidal disruption of stars by the supermassive black hole based on the evolving radii of the stars, however, has a significant effect on the system. The distribution of giant stars within the central parsec is reduced and a loss cone develops wherein none of the stellar population resides. It is believed that the loss cone grows outward corresponding to the stellar evolution at such a rate that late-type stars are tidally disrupted before stellar collisions can occur. This hole that develops appears as a flat density slope in the plain of the sky. This model is able to explain the flattened profile of late-type stars found in Buchholz et al. (2009) and Do et al. (2010) with the destruction of giant stars by tidal disruption.

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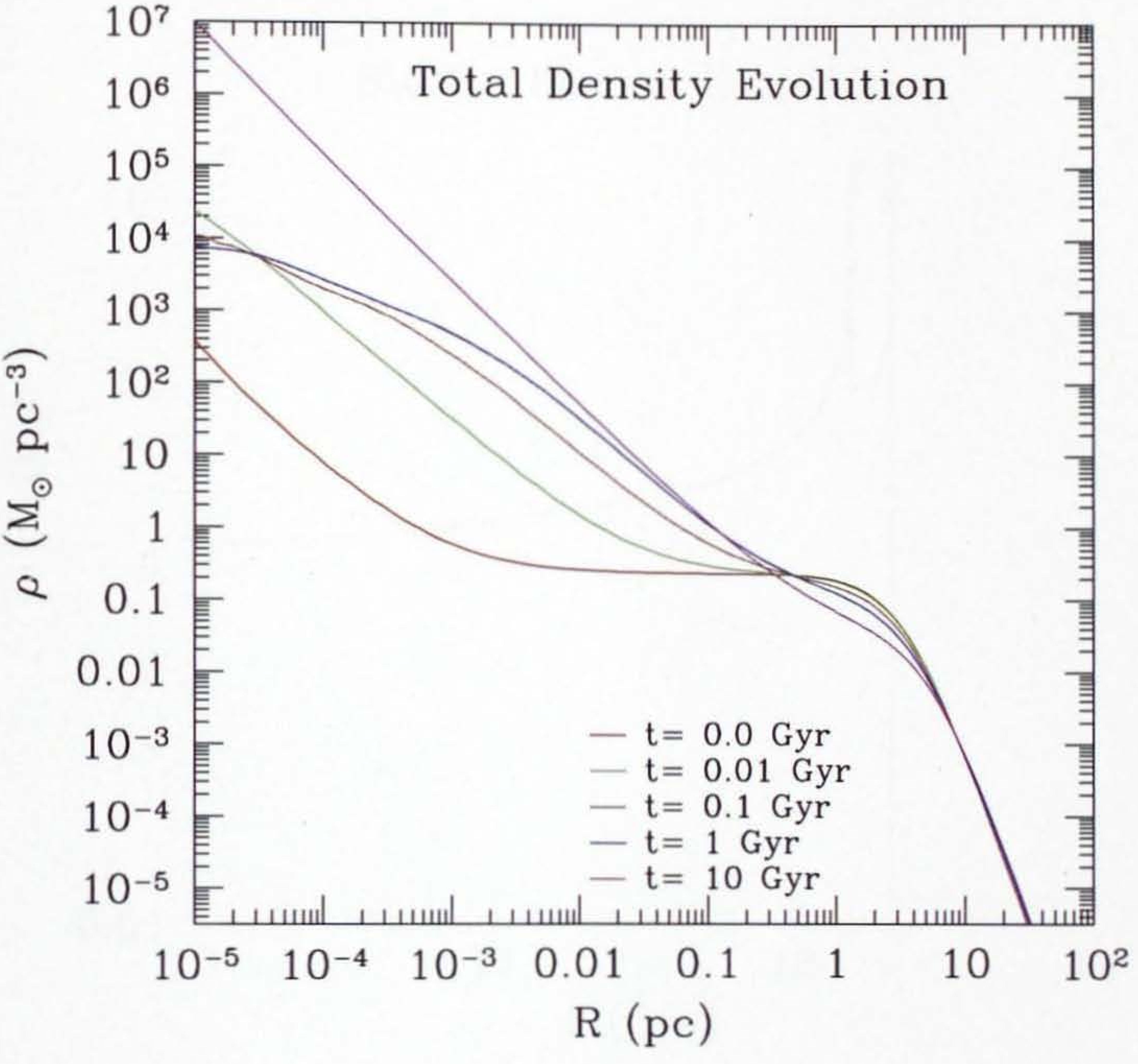

Fig. 1.— The time evolution of the total density of the Galactic Nucleus, as a function of distance from the center. The model begins with a modified plummer model. As the model progresses, the Fokker-Planck equation allows for the distribution to change. By 10 billion years the system has become dynamically relaxed with a power relation of $\gamma = 7/4$.

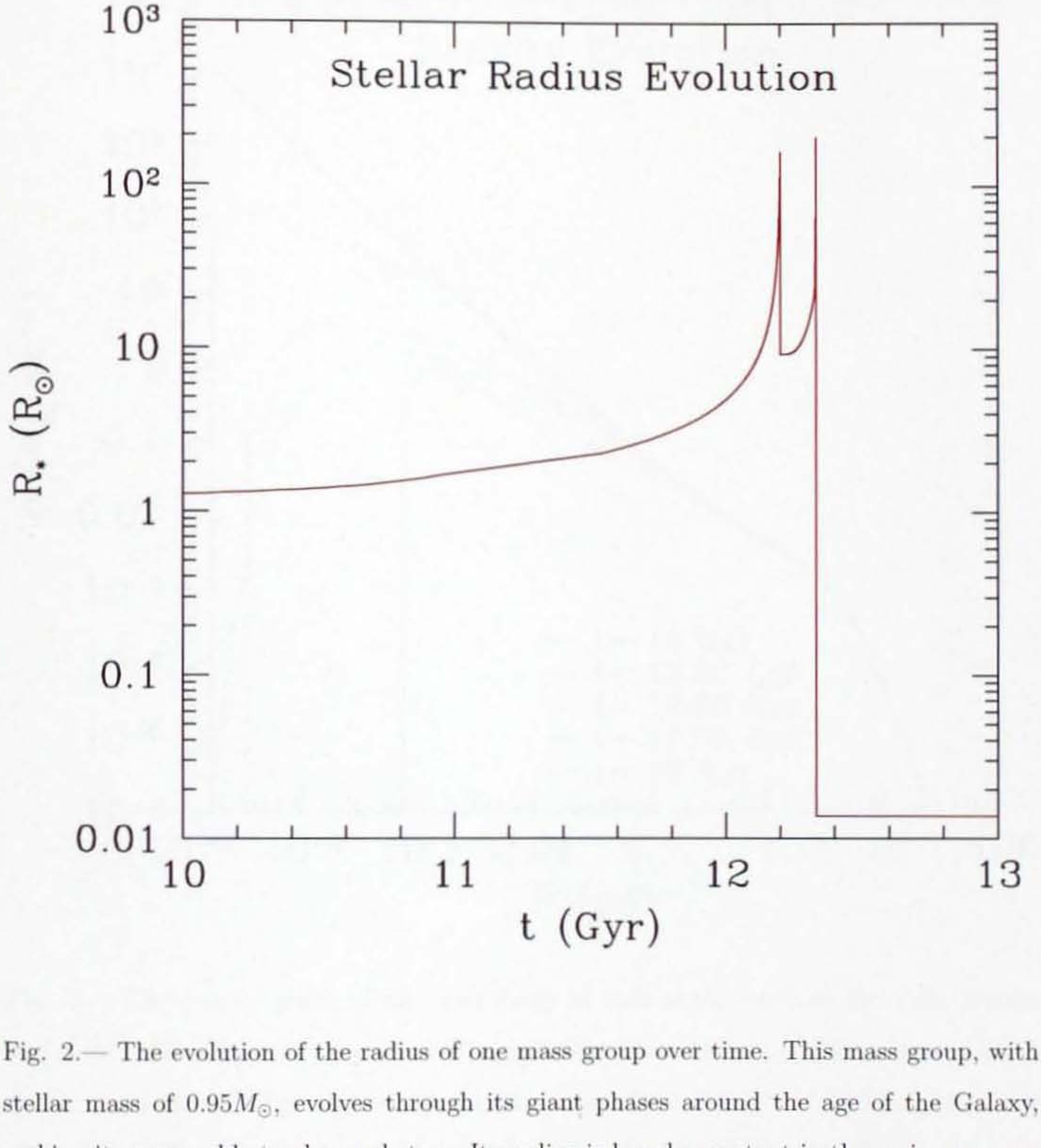

Fig. 2.— The evolution of the radius of one mass group over time. This mass group, with stellar mass of $0.95M_\odot$, evolves through its giant phases around the age of the Galaxy, making it comparable to observed stars. Its radius is largely constant in the main sequence phase, increases dramatically in the red giant phase, reduces during the horizontal branch, and reaches its maximum at the climax of the AGB phase. The star's radius is greatly diminished in its final phase: white dwarf.

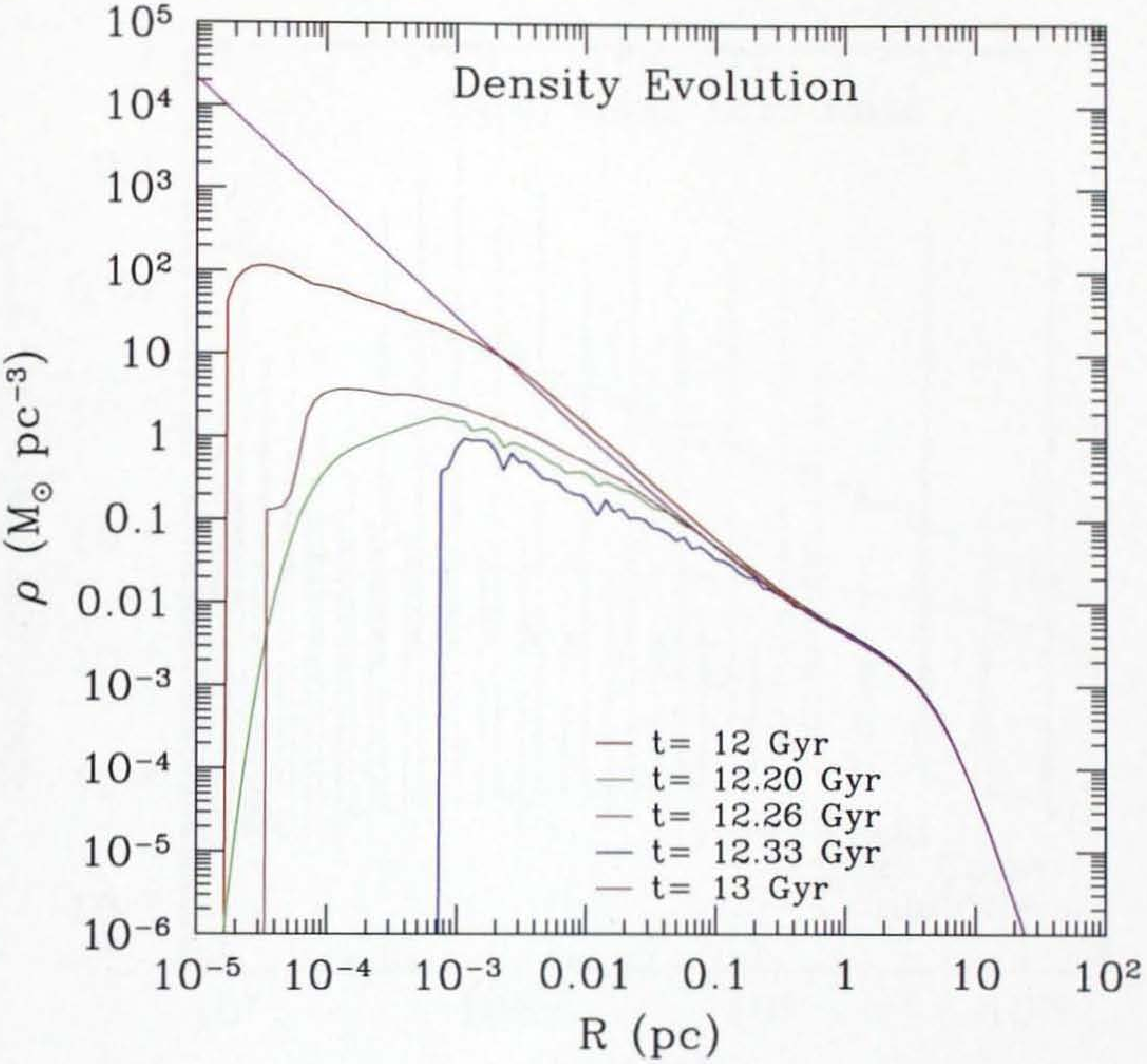

Fig. 3.— The density profile of the mass group at each of the star's evolutionary phases. Red is the main sequence phase, green is immediately following the red giant phase, peach is during the horizontal branch phase, blue is the climax of the AGB phase, and magenta is the white dwarf phase. As the stars in the mass group evolve, the density changes due to stellar collisions, tidal disruptions, and drift cause by stellar interactions. Tidal disruptions prevent stars from existing within the Roche limit from the center, causing the sudden drop in the density profile. Drift can allow stars to refill these arreas when the Roche limit decreases, as with the horizontal branch and white dwarf stars. Evidence of this is also seen in the red giant profile due the stellar radius having just passed its peak.

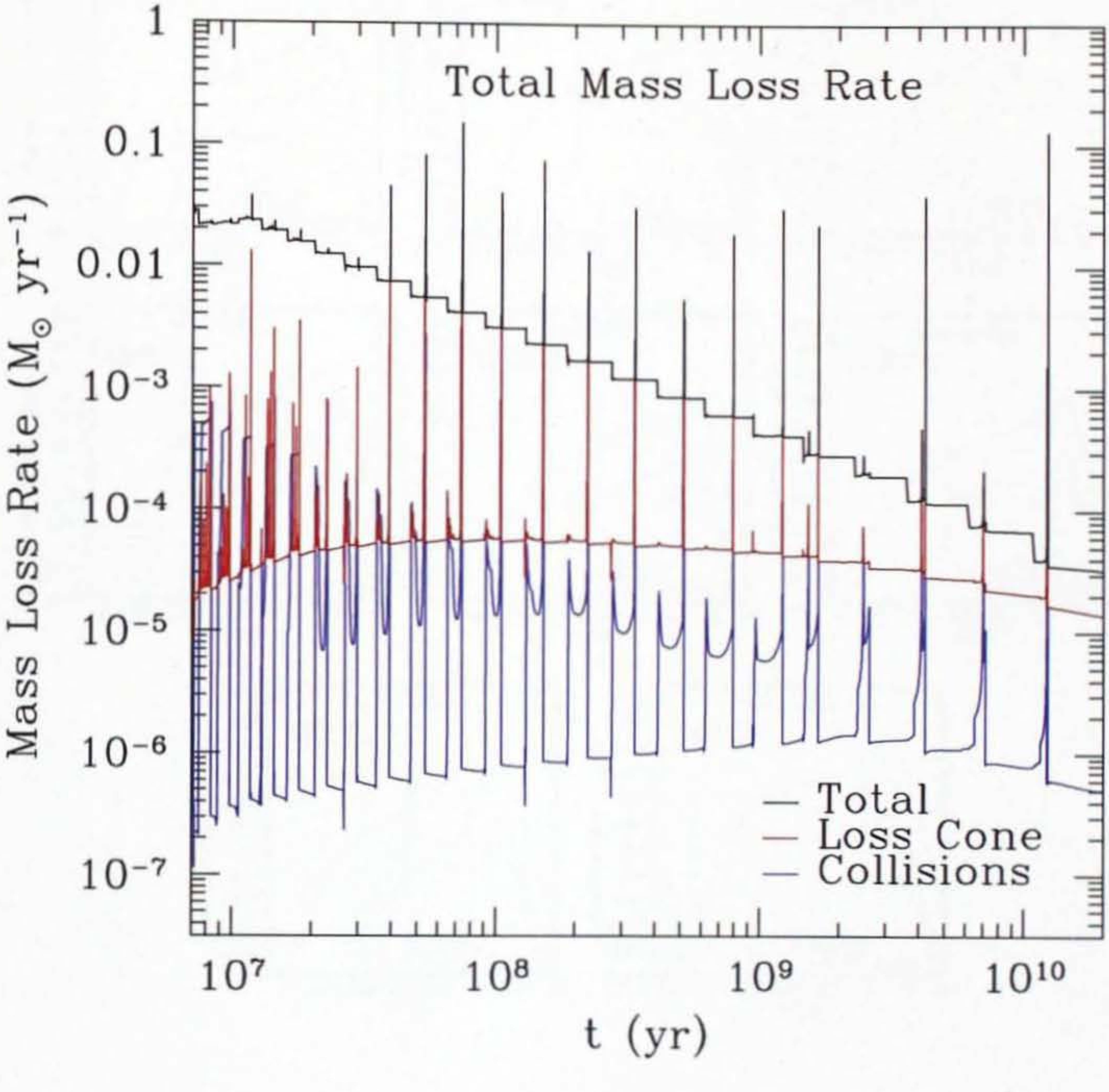

Fig. 4.— The total mass loss rate of the system as it changes over time. The black line represents the total mass loss rate by tidal disruptions, stellar collisions, and stellar evolution from all mass groups. The red line represents the total mass loss rate due to tidal disruptions alone, and the blue line represents the total rate for mass loss by collisions. The total line has a step-like function due to the binning of masses into discrete mass groups. The sudden peaks in the loss cone and collision lines correspond to changes in stellar evolution of the mass groups.

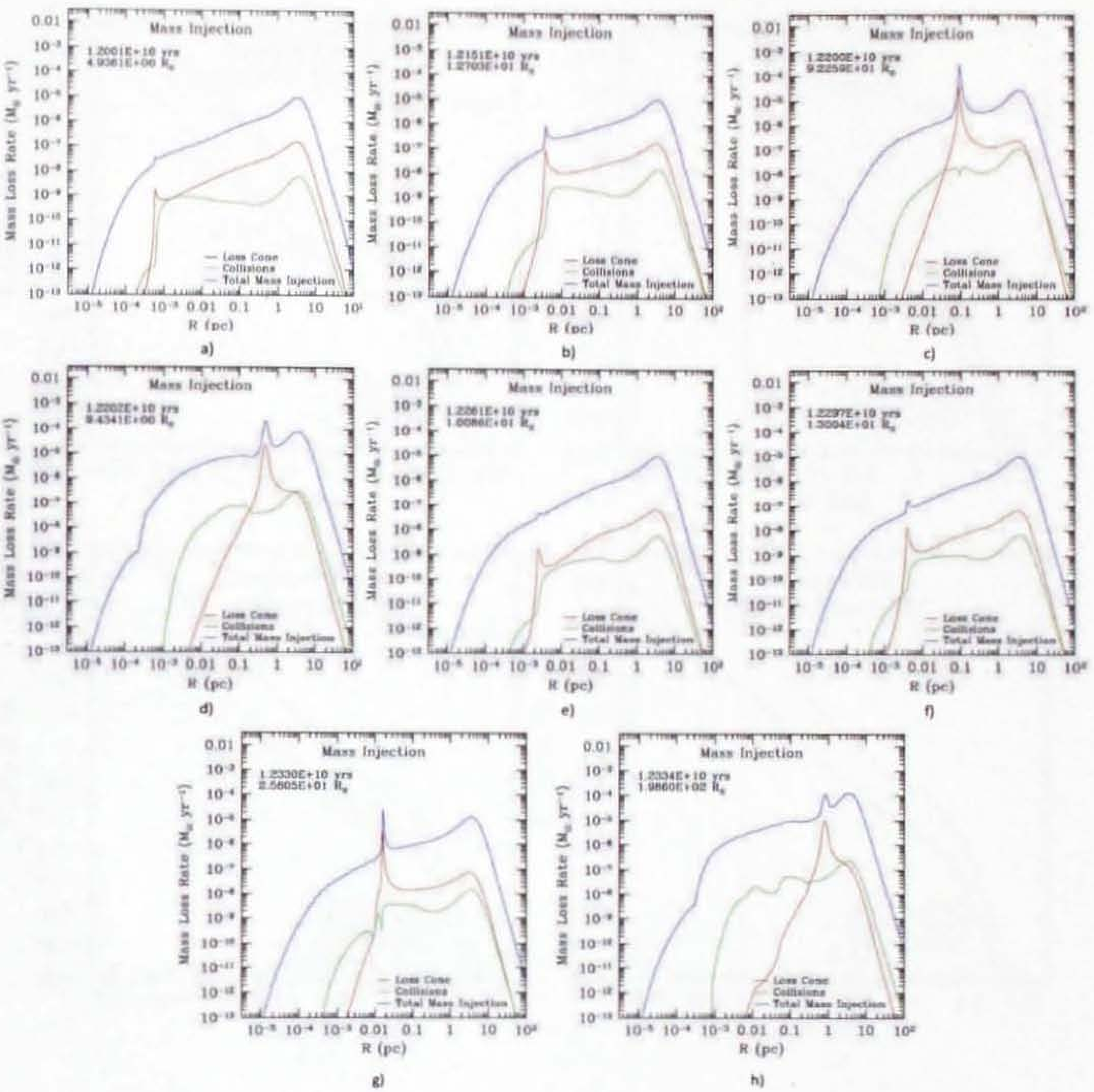

Fig. 5.— The mass loss rates as a function of distance from the center at specified times. The red line represents the rate from the loss cone for the mass group, the green line represents the rate from collisions for the mass group, and the blue line is the combined rate from loss cone and collisions for all mass groups. In plot *a)* the mass group is the main sequence phase. In *b)* and *c)*, the mass group is evovling through the red giant phase, and in *d)* it has just passed the apex of the phase. Plot *e)* captured the mass group in the horizontal branch, and plots *f)* through *h)* show the mass group ascends to the top of the AGB phase. Note how the loss cone mass rate forms a peak that moves out as the radius of the stars increase.

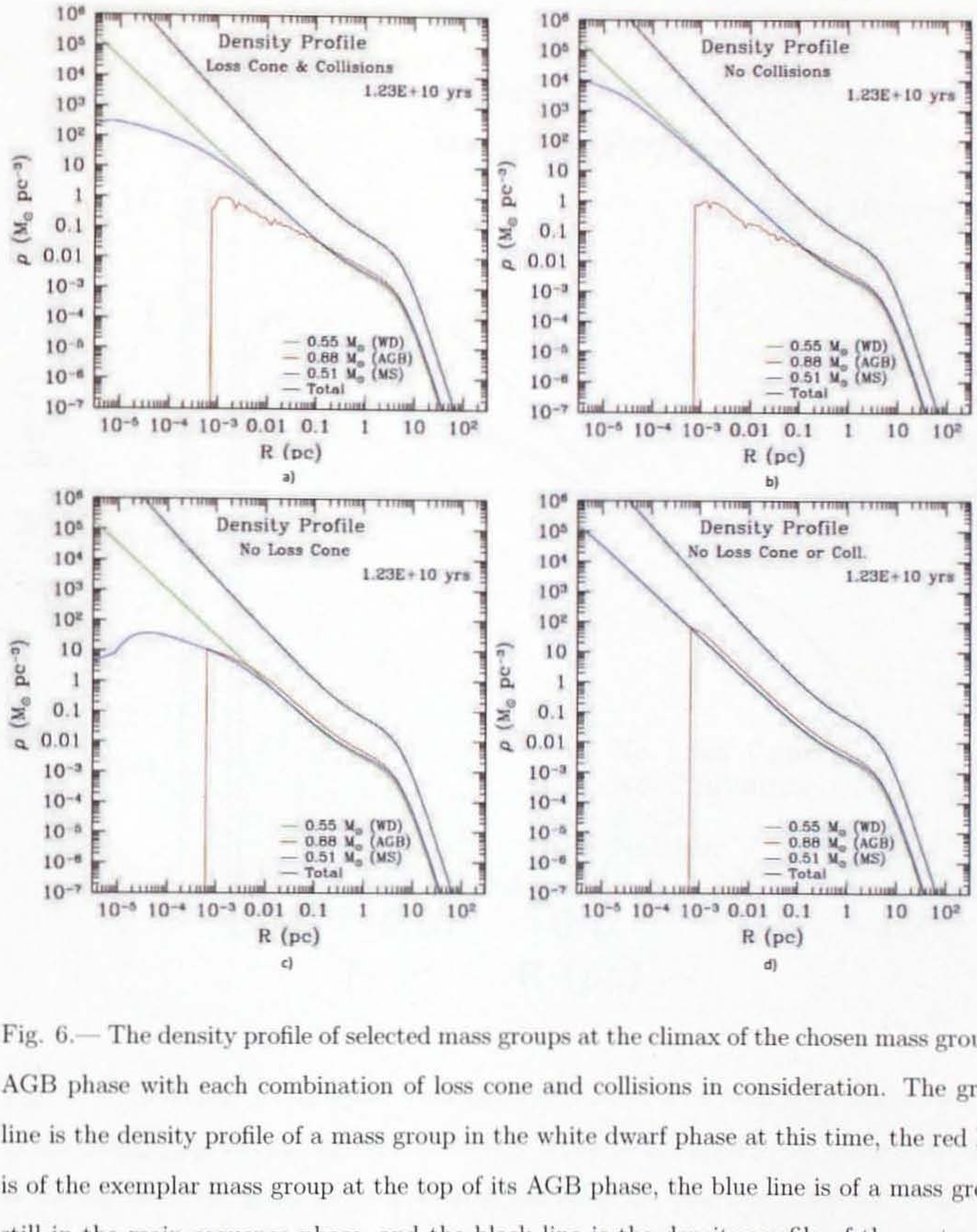

Fig. 6.— The density profile of selected mass groups at the climax of the chosen mass group's AGB phase with each combination of loss cone and collisions in consideration. The green line is the density profile of a mass group in the white dwarf phase at this time, the red line is of the exemplar mass group at the top of its AGB phase, the blue line is of a mass group still in the main sequence phase, and the black line is the density profile of the system at this time. Plot *a)* allows for both tidal disruptions and collisions to remove mass from the system. Plots *b)* and *c)* show the density profiles when collisions and the loss cone are turned off in the model, respectively. The plot *d)* shows the densities as a function of distance from the center when both loss cone and collisions are removed from the model.

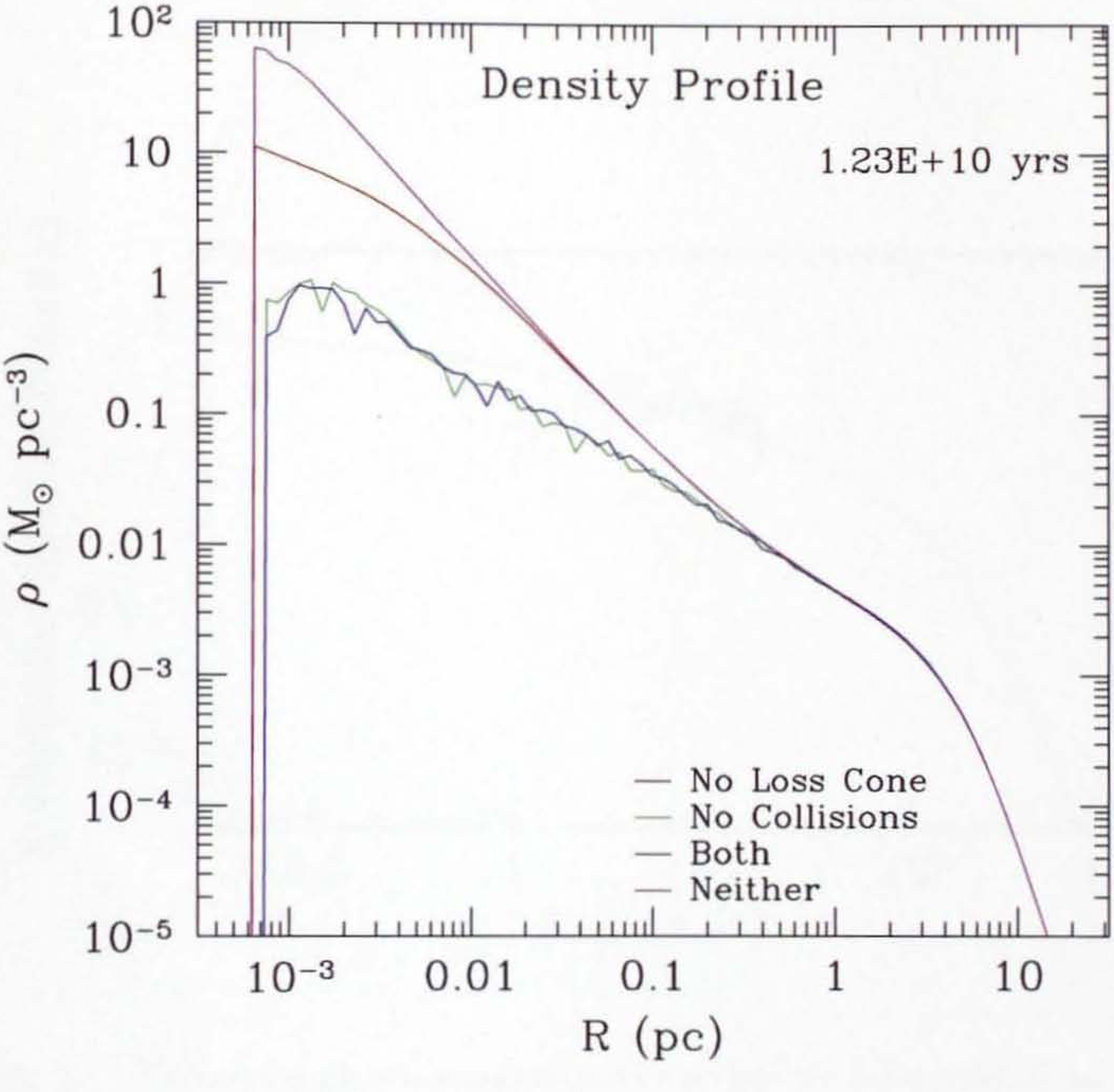

Fig. 7.— The density profile of the mass group at the end of its AGB phase around the age of the Galaxy. The red line signifies the density profile of this mass group without the effect of the loss cone, the green shows it without collisions, the blue line represents when both loss cone and collisions are included, and the magenta line corresponds to the density profile with neither mechanisms included.

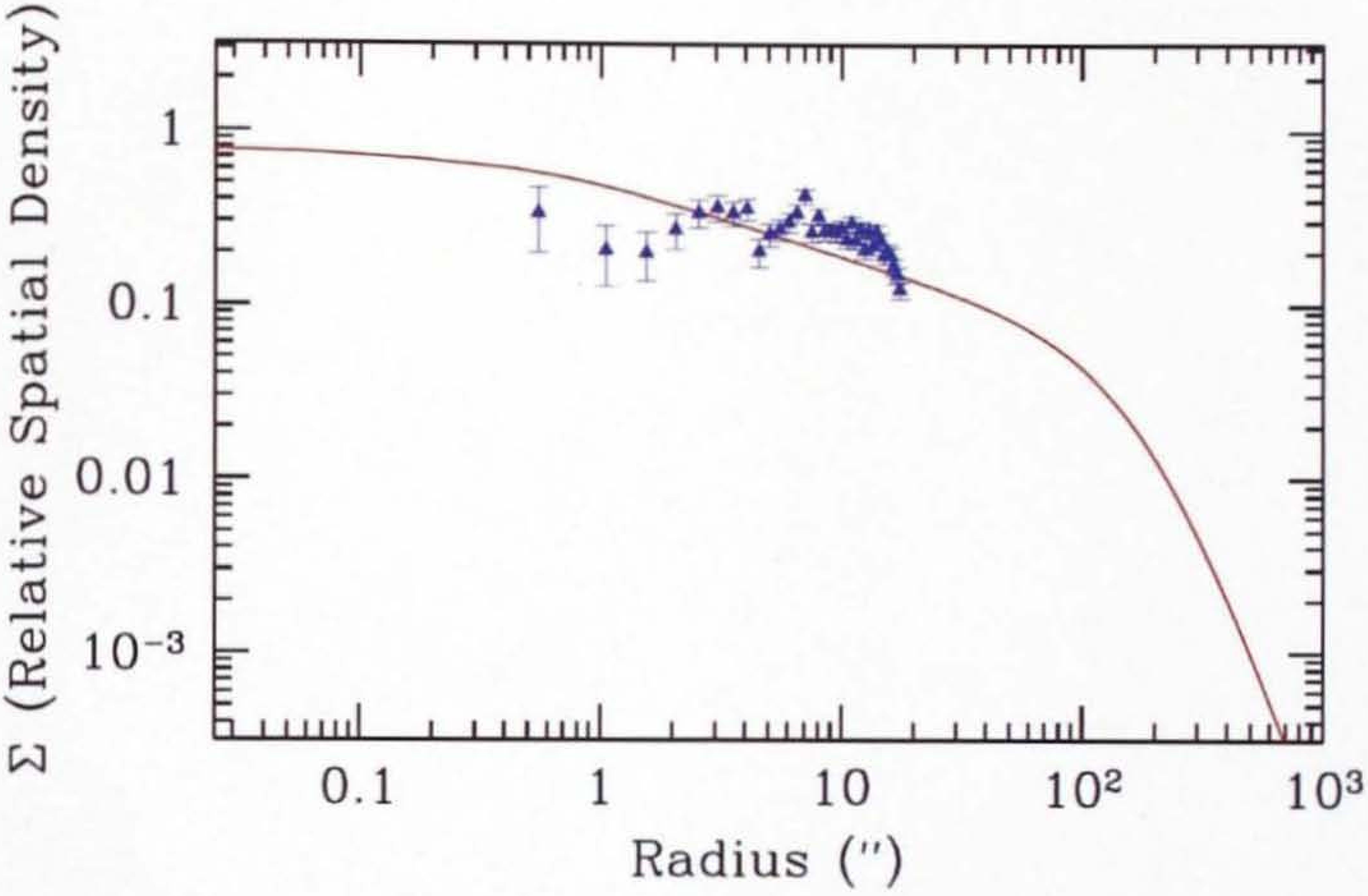

Fig. 8.— The density profile of post-main-sequence stars from the model projected into the plane of the sky. Data are late-type stars from Buchholz et al. (2009).