MODEL ATMOSPHERES FOR IRRADIATED GIANT STARS: IMPLICATIONS FOR THE GALACTIC CENTER

RAUL JIMÉNEZ, 1 JULIANA P. DA SILVA, 2, 3 S. PENG OH, 4 UFFE G. JØRGENSEN, 3 AND DAVID MERRITT 5

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ABSTRACT

Irradiation of a stellar atmosphere by an external source (e.g., an AGN) changes its structure and therefore its spectrum. Using a state-of-the-art stellar atmosphere code, we calculate the infrared spectra of such irradiated and transformed stars. We show that the original spectrum of the star, which is dominated by molecular bands, changes dramatically when irradiated even by a low-luminosity AGN \((L_X = 10^{33} \text{ ergs s}^{-1})\), becoming dominated by atomic lines in absorption. We study the changes in the spectrum of low-mass carbon- and oxygen-rich giant stars as they are irradiated by a modest AGN, similar to the one at the Galactic center (GC). The resulting spectra are similar to those of the faintest S-cluster stars observed in the GC. The spectrum of a star irradiated by a much brighter AGN, like that powered by a tidally disrupted star, is very different from that of any star currently observed near the GC. For the first time, we have discovered that the structure of the atmosphere of an irradiated giant changes dramatically and induces a double inversion layer. We show that irradiation at the current level can explain the observed trend of CO-band intensities decreasing as a function of increasing proximity to Sgr A*. This may indicate that (contrary to previous claims) there is no paucity of old giants in the GC, which coexist simultaneously with young massive stars.

Subject headings: Galaxy: center — stars: winds, outflows

1. INTRODUCTION

The fact that UV radiation and X-rays can alter the atmospheres of stars has been recognized for more than 30 years (Davidson & Ostriker 1973; Basko & Sunyaev 1973; Arons 1973; Basko et al. 1974; Fabian 1979). Irradiation by a source such as an active galactic nucleus (AGN) will produce an increase in the atmospheric temperature and in the mass-loss rate (Edwards 1980; Voit & Shull 1988; Chiu & Draine 1998). Even a modest level of irradiation from a low-luminosity AGN, such as the one currently at the center of the Milky Way, can be sufficient to destroy molecules formed in the atmosphere of cool giant stars, thus transforming their spectrum without inducing significant mass loss. Recently, Barman et al. (2004) carried out detailed computations of the atmospheric structure of an M dwarf irradiated by a hot stellar companion (a precataclysmic variable). However, up to now, despite recent advances in the calculation of molecular opacities (Jørgensen 2005) and in stellar modeling algorithms, no detailed computations of the atmosphere of a cool giant star that is irradiated by an external source have been performed.

In this paper, for the first time, we compute the stellar spectrum and atmospheric structure of a cool \((\sim 4000 \text{ K})\) giant (both carbon- and oxygen-rich) star in the presence of an AGN. Our stellar atmosphere code includes a complete frequency-dependent description of the atomic and molecular lines that dominate the infrared (IR) spectrum. Our computational approach is general, but we focus here on the spectrum of a star that is irradiated by a source at the Galactic center (GC). We are motivated by the recent discovery (Revnivtsev et al. 2004) that the GC may have been a low-luminosity AGN \((L \approx 10^{39} \text{ ergs s}^{-1})\) as recently as a couple of hundred years ago. In addition, recent estimates of the rate of stellar tidal disruptions by the GC supermassive black hole (SBH; Wang & Merritt 2004; Merritt & Szell 2005) suggest a rate of the order of one event per \(10^4 \text{ yr}\) or higher for solar-mass stars. Tidal disruption of a star by a SBH is expected to produce an extremely luminous event, \(L \approx 10^{44} \text{ ergs s}^{-1}\), with a duration of weeks or months (e.g., Komossa 2002).

The GC SBH was recently found to be surrounded by a cluster of apparently young stars. For one of these stars, S0-2, an IR spectrum showed no CO absorption, but possible He\(\text{I}\) absorption (Ghez et al. 2003). The latter indicates that the star cannot have an effective temperature less than about 15,000 K (Hanson et al. 1996). The orbit of S0-2 has a pericenter distance of \(\sim 100 \text{ AU}\) and an apocenter distance of \(\sim 1000 \text{ AU}\). The presence of the He\(\text{I}\) line and the absence of CO point to S0-2 being young, with spectral class in the domains O and B. The case for hot stars so close to the GC has been further reinforced by Eisenhauer et al. (2005), who obtained high signal-to-noise ratio (S/N) spectra of 17 S-cluster stars. For the brightest stars in this sample, spectra clearly show the presence of the He\(\text{I}\) line at 2.1127 \(\mu\text{m}\). However, for stars with \(K > 15\), the line is not present. Hence, the spectral properties of the S-cluster stars are not uniform. If these stars are actually young (a few Myr), their formation so close to GC SBH is a serious theoretical challenge (Phinney 1989). One possible explanation is that these stars are not young, but old, and that their atmospheres have been modified by some physical mechanism, such as stellar collisions, tidal stripping, or external radiation (e.g., Genzel et al. 2003; Alexander & Morris 2003; Hansen & Milosavljević 2003; see also the review by Alexander 2005 and references therein).

In this work, we compute the detailed spectrum of giant stars irradiated by an AGN in the luminosity range \(10^{33} - 10^{44} \text{ ergs s}^{-1}\), integrated over the range 2–200 keV (hereafter we denote the luminosity in this range by \(L_X\)). In particular, we show how these old giants are affected by low-luminosity AGNs \((L_X \approx 10^{39} \text{ ergs s}^{-1})\), such as the one that may have been present at the GC in the recent past, and also by the high luminosity \((L_X \approx 10^{44} \text{ ergs s}^{-1})\) that is believed to accompany the tidal disruption of a star by the SBH. We find that the spectrum of an irradiated old giant star is...
similar to that of the faintest S-cluster stars ($K > 15$) observed by Eisenhauer et al. (2005). However, we are unable to transform the spectra of cool giants such that they resemble those of the brightest S-cluster stars for a low-luminosity AGN ($L_\gamma < 10^{39}$ erg s$^{-1}$). Higher luminosities, however, such as the one from a tidally disrupted star, are sufficient to heat up the stellar atmosphere above 15,000 K and therefore produce the He i line. However, the total destruction of molecular lines in the spectra of these giants seems to point out that the deficiency of giants in the GC (Sellgren et al. 1990; Genzel et al. 1997; Eckart et al. 1999; Figer et al. 2000; Gezari et al. 2002) might not be such. We show that, within our model, irradiation explains the decreasing CO-band intensity observed as a function of radius from Sgr A*. The other main result of our study is that we find a double layer inversion in the atmospheres of irradiated giants for irradiation fluxes $f > 10^2$ ergs s$^{-1}$ cm$^{-2}$ on the surface of the star.

We demonstrate that even if the AGN was shining at or near the Eddington luminosity for $10^6$ yr, due to the high eccentricity of the S-cluster stars orbits, the amount of irradiation is most likely not sufficient to make the He i line appear. On the other hand, stars on more circular orbits could be sufficiently transformed to reproduce the spectral properties of the brightest S-cluster stars (including the He i line).

2. IRRADIATION OF STELLAR ATMOSPHERES: THE IR SPECTRUM

If the atmosphere of the star is sufficiently irradiated, the energy deposited in the atmosphere will heat up the outer layers and produce a wind. Basko & Sunyaev (1973) constructed a semi-analytic model to account for the effects of irradiation on a stellar atmosphere. The most obvious consequence of irradiation is that the temperature of the area of the star facing the AGN increases by $T_i / T_e \sim 1 + F_X / F_i^{3/4}$. At the microscopic level, the X-rays photoionize He i and He ii and O, C, Ne, N, Fe and their ions. Below 5000 K, the main source of opacity is due to photo-detachment of H$^-$, while above this temperature, opacity is dominated by photoionization of oxygen and carbon. Basko & Sunyaev (1973) find that in their models the envelope develops a significant wind, although most of the energy is reradiated. By integrating the hydrodynamic equations, Voit & Shull (1988) calculated the rate at which mass is lost from the envelope of red supergiants. We use their work to estimate the mass-loss rate from giant atmospheres in § 3.

However, in order to compare with the observations of Eisenhauer et al. (2005), we are interested in computing detailed spectra of irradiated stars. For this purpose we have used a stellar atmosphere code (Jørgensen et al. 1992) that is based on the MARCS code (Gustafsson et al. 1975). The models are computed in hydrostatic equilibrium, with radiative and convective energy transport included. Plane-parallel and spherical geometry are considered where appropriate. The radiative transfer includes neutral and singly ionized atomic lines from the VALD database and molecular opacities from CO, C2, CN, CS, HCN, C2H2, C3, SiO, TiO, H2O, and several diatomic hydrates (Jørgensen 2003, 2005, and references therein). All opacities are treated by the opacity sampling technique (Helling & Jørgensen 1998). The atmospheric structure and the spectra are computed separately (in order to allow studies of the contribution of various species to the spectra individually), but consistently, and are based on the same line lists. A new feature of the version of the code used for the present paper is the treatment of external illumination, which we have based on the inclusion of an improved version of the subroutines developed and described by Alencar et al. (1999), Nordlund & Vaz (1990), and Vaz & Nordlund (1985).

For reference, we first compute the spectra of nonirradiated oxygen-rich (C/O = 0.0, $T_{\text{eff}} = 4000$ K, log $g = 2.0$, $Z = Z_\odot$) and carbon-rich (C/O > 1) stars. We then consider an irradiated star. The irradiation source is taken to be the GC with an AGN spectral shape as given by Sazonov et al. (2004). In particular, we use their equation (14) for the energy range $1 \text{ eV} < E < 2 \text{ keV}$, their equation (8) for $E > 2 \text{ keV}$, and their equation (23) for $E < 1 \text{ eV}$. The total flux for Sgr A*, assuming a mass of $3.7 \times 10^6 M_\odot$, is $L = 5.0 \times 10^{39}(f_{\text{edd}}/10^{-4})$ ergs s$^{-1}$ (Ghez et al. 2005). Although the Sazonov et al. (2004) spectral energy distribution is for typical QSOs, we use it here as a good approximation to describe the AGN at the GC. Our results are not sensitive to moderate changes in the parameters that describe the spectral energy distribution of QSOs in Sazonov et al. (2004). For $f_{\text{edd}} = 10^{-4}$, the luminosity of the AGN at the GC corresponds roughly to the estimate by Revnivtsev et al. (2004) for the luminosity of the GC a few hundred years ago.

The IR spectrum (2 – 2.4 $\mu$m) for the nonirradiated case is shown in Figure 1 for the oxygen-rich model. The top panel shows the atomic lines, the second panel the CO bands, the third panel other molecular bands, and the bottom panel the total spectrum. Clearly, the IR spectrum of an oxygen-rich giant is dominated mainly by molecular bands, but also shows some atomic lines. The most prominent of these atomic lines is the Br$\gamma$ line at 2.1661 $\mu$m. Note that there are no emission lines. It is also worth mentioning that there are no CO lines in the 2 – 2.3 $\mu$m range; they appear only at wavelengths beyond 2.3 $\mu$m. Therefore, these strong bands would not be observed in the spectra of Ghez et al.

![Figure 1](https://example.com/figure1.png)
However, they are in the range observed by Genzel et al. (1997), Eckart et al. (1999), Figer et al. (2000), Gezari et al. (2002), and Eisenhauer et al. (2005), and we do a detailed comparison in §4. While the molecular bands are somewhat stronger than those observed in the faintest S-cluster stars, the spectrum of a nonirradiated oxygen-rich giant is not too dissimilar from the ones observed for the faint stars in the S-cluster sample (see Fig. 1 in Ghez et al. [2003] and Fig. 5 in Eisenhauer et al. [2005]). Figure 2 shows the nonirradiated spectrum for a carbon-rich star. Note the absence of CO lines below 2.3 μm (they are very strong CO bands beyond this wavelength) and the increase in the strength of the other molecular bands. Clearly, the nonirradiated spectrum of a C-rich giant does not resemble any of the observed S-cluster stars at all.

We then irradiate the star as described above, assuming different incident fluxes. Figure 3 assumes an orbit-averaged flux, $f_0 = 2 \left( \frac{L}{10^{33} \text{ ergs s}^{-1}} \right) \left( \frac{f_{\text{supp}}}{0.6} \right) \left( \frac{r_{\text{min}}}{100 \text{ A.U.}} \right) \text{ ergs s cm}^{-2}$, (1) where $r_{\text{min}}$ is the pericenter distance. See equation (6) and Figure 7 for a definition of $f_{\text{supp}}$. On the other hand, Figure 4 assumes a flux of $f = 10^2 f_0$, corresponding to a star illuminated by Sgr A* during a more active state, when $L \approx 10^{35}$ ergs s$^{-1}$, still smaller than the luminosity estimated by Revnivtsev et al. (2004) for the luminosity of the GC a few hundred years ago. Our illuminated atmospheric models are static, and we are not able to compute models with illumination fluxes larger than $f = 10^2 f_0$. For this, dynamic models are required, which we are currently constructing. However, even for $f = 10^2 f_0$ the transformation of the spectrum is significant.

The first thing to note from Figure 3 is the decrease in the strength of the molecular lines, even for $f = f_0$. Note also the reduction of the CO-band intensity. If we examine the spectrum of the star for $f = 10^2 f_0$ (Fig. 4), we notice even more significant changes. As expected, all the molecular bands are gone, including the CO bands. However, now some of the atomic lines are in emission due to the stronger irradiation. In particular, the Brγ line at 2.1661 μm is now in emission. At this small distance, irradiation results in a rise in the temperature of the atmosphere at $\tau_{\text{Ross}} = 10^{-4.9}$ from 2500 to 8000 K. However, the He i line at 2.11 μm is clearly not present, and more importantly, no other line in the irradiated star appears at the same wavelength.

It is clear that S-cluster stars irradiated at their present orbits ($5 \times 10^{-4}$ to $5 \times 10^{-3}$ pc) by a low-luminosity AGN a few hundred years ago do not resemble the spectra of any of the observed S-cluster stars seen today (Ghez et al. 2003; Eisenhauer et al. 2005). Their spectra would be totally dominated by emission lines. On the other hand, if we look at Figure 3, which is equivalent to a star irradiated at a distance of a few hundred AU, with a luminosity of $L_X \sim 10^{33}$ ergs s$^{-1}$, the similarity to the faintest stars of the Eisenhauer et al. (2005) sample is striking. In this case, the He i line is absent, and the deepest absorption feature in the spectrum is dominated by the Brγ line.

It is clear that after the level of irradiation suggested by Revnivtsev et al. (2004) has ceased, the star will cool down and readjust to its previous equilibrium situation in a few years (as soon as the temperature is low enough, about 2000 K, molecules will form immediately, on a timescale of seconds). However, the presence of illumination will stop convection in the atmosphere. It takes of the order of a few hundred years for convection to be

![Fig. 2.—Same as Fig. 1, but for a carbon-rich giant. Note that CO lines are only present beyond 2.3 μm, while the other molecules get considerably stronger than for an oxygen-rich star.](image1)

![Fig. 3.—IR spectrum of an irradiated oxygen-rich star illuminated with a flux $f = f_0$. Top, atomic lines; second, CO lines; third, other molecules; bottom, total spectrum. Note the decrease in the strength of the molecular lines with respect to the nonirradiated spectrum of Fig. 1.](image2)
restored and therefore the temperature in the outer layers to decrease enough to allow molecules to re-form. This argument also ensures that the timescale of molecule formation is longer than the rotation timescale of the stars, assuring that molecules will be wiped out over the whole surface of the star. Note, however, that the present X-ray flux from the GC is sufficient to destroy molecules, as shown in Figure 3.

Figure 5 shows the temperature versus gas pressure model structure for a oxygen-rich giant for \( f = 0, f_0, \) and \( 10^2 f_0. \) In the moderately irradiated model \( f = f_0 \) from the GC (as well as in the nonirradiated model), the upper layers are relatively dense (\( P_{\text{gas}} \approx 100 \text{ dyn cm}^{-2} \)). Therefore, the absorption of radiation from the SBH at the GC is already substantial in the top of the atmosphere. As a result, the model structure resembles a photospheric-chromospheric atmosphere with a slowly rising, almost flat, chromospheric temperature distribution. The inner part of the atmosphere is almost unaffected by the illumination at \( f = f_0. \) For \( f = 10^2 f_0, \) the radiation is strong enough that the atmosphere is heated at all optical depths in the atmospheric model, and the chromospheric temperature rise is substantial. As a result, the degree of ionization increases, making the continuous opacity increase, whereby the atmosphere expands (considerably). Figure 6 shows the relative fraction of neutral (\( \text{C}\,\text{i} \)) and singly ionized (\( \text{C}\,\text{ii} \)) carbon (two right panels) for the three models in Figure 5. Other atoms, including H, N, O, Al, Si, S, Ca, and Ni, behave qualitatively similarly (whereas Ca, Mg, Cr, and Fe are substantially doubly ionized in the top layers, and He is neutral throughout the atmosphere). The main contributor of free electrons is hydrogen, and the total abundance and pressure of electrons are shown in the two left panels. It is seen that the degree of ionization (and the abundance of free electrons) increases rapidly outward from \( \log \tau_{\text{Ross}} \approx 0 \) to \( -2. \) This is the region of temperature rise in the strongly irradiated model (\( \log P_{\text{gas}} \) from \( \approx 3 \) to 0). From \( \log \tau_{\text{Ross}} = -2 \) and outward, hydrogen is fully ionized, and the electron density and pressure therefore now again decrease outward. As a consequence, the opacity decreases in the outermost layers, and the energy deposition due to external illumination also decreases outward from \( \log P_{\text{gas}} = 0 \) onward. The temperature therefore decreases toward the surface from this point onward, just like in a normal photospheric model. This feature is not seen in any chromospheric model heated from below. It is peculiar to strongly irradiated atmospheres.

3. MASS LOSS FROM AGN IRRADIATION

In this section, we consider whether the heat input from AGN irradiation is sufficient to evaporate the stellar envelope of a star, causing an observable change in its spectrum. We consider much larger AGN luminosities than in \( \S \) 2, up to \( \sim 0.5\% L_{\text{Edd}}. \) This assumption is motivated by the very high luminosities believed to accompany stellar tidal disruptions (Komossa 2002) and the estimated high rate of such events (Wang & Merritt 2004; Merritt & Szell 2005), one per \( 10^3 - 10^4 \) yr or so.
This is a radiative rather than a gravitational (e.g., Davies & King 2005) mechanism for stripping stellar envelopes off stars near the GC. If the effective temperature is only raised to about $T_{\text{eff}} \approx 15,000$ K (which is high enough to produce the observed He I line), then these modified stars could explain the observed S-cluster stars, although stars with higher effective temperatures will have lifetimes that are too short to account for the number of stars observed (see eq. [2] in Goodman & Paczynski 2005). Note that stripping the envelope is a different mechanism from the one proposed in the previous sections of this work, where the temperature of the stellar atmosphere was raised due to illumination without mass loss. It is this constant illumination that keeps the stellar atmosphere hot. In the stripping scenario, there is no source of heating, and the star will cool down to a new equilibrium configuration.

Regarding, it is still interesting to explore the consequences of the mass loss, as it will be a useful marker of the past activity of Sgr A*. This mechanism will clearly predict a characteristic dependence of the number of “hot” stars on pericentric radii. Stripping the envelope off a star exposes its hotter core and thus increases its effective temperature. However, the luminosity of the star will be unaffected, since the conditions in the stellar core are effectively decoupled from the conditions in the envelope. With numerical stellar models (Jimenez et al. 2004), we compute the effective temperature $T_{\text{eff}}$ of the stripped star and its new radius $R_{\text{e}}$, assuming $L = 4\pi R_{\text{e}}^2 T_{\text{eff}}^4 = \text{const}$.

Can the entire envelope be stripped due to a close encounter with an AGN? Voit & Shull (1988) consider the X-ray–induced mass loss from stars near AGNs. They consider mass loss due to two mechanisms: thermal winds driven by X-ray heating and stellar ablation by radiation pressure. For thermally driven winds, they directly integrate the hydrodynamic equations and find that the formula

$$M_{\text{thermal}} = 5.0 \times 10^{-6} \ M_\odot \text{ yr}^{-1} L_{42}^{0.9} R_{15}^{1.8} R_{100}^{-4}$$

reproduces their results very well, as well as the previous analytic results of Basko et al. (1977). Here $L_{42} = L/(10^{42}$ ergs s$^{-1}$) is the AGN luminosity, $R_{15} \equiv R_*/10^{15}$ cm is the distance of the star from the AGN, and $R_{100} \equiv R_*/(100 R_\odot)$ is the stellar radius. Note that this calculation assumes that emission-line cooling is quenched in the wind and is therefore potentially an overestimate. They find that ablative mass loss (which is independent of emission-line cooling), is

$$M_{\text{abl}} \approx 3.8 \times 10^{-6} \ M_\odot \text{ yr}^{-1} L_{42} R_{15}^{-2} M_*/^{1/2} R_{100}^{5/2}$$

TABLE 1

| Star | $r_{\text{min}}/$AU (2) | $e$ (3) | $\Delta M/M_\odot$ (4) | $T_{\text{eff}}$/K (5) | $\Delta M/M_\odot$ (6) | $T_{\text{eff}}$/K (7) |
|------|------------------------|--------|------------------------|----------------------|------------------------|----------------------|
| S2   | 120                    | 0.87   | 0.31                   | 6400                 | 0.47                   | 7900                 |
| S12  | 220                    | 0.73   | 0.18                   | 5300                 | 0.22                   | 6300                 |
| S14  | 100                    | 0.97   | 0.29                   | 6200                 | 0.51                   | 8100                 |
| S1   | 2020                   | 0.62   | 0.35                   | 3900                 | 0.07                   | 4900                 |
| S8   | 180                    | 0.98   | 0.15                   | 5100                 | 0.30                   | 6900                 |
| S13  | 1000                   | 0.47   | 0.09                   | 4400                 | 0.14                   | 5600                 |

Notes.—The orbital parameters are from the fits of Eisenhauer et al. (2005). We assume the AGN shines with a luminosity $L = 10^{43}$ ergs s$^{-1}$ for $\sim 10^6$ yr. Cols. (4)–(5) are for a 1 $M_\odot$ star with an initial $T_{\text{eff}} = 3000$ K and $R_{100} = 1$. Cols. (6)–(7) are for a 2 $M_\odot$ star with an initial $T_{\text{eff}} = 4000$ K and $R_{100} = 1.23$.

for $R < R_{\text{abl}}$, where

$$R_{\text{abl}} = 6.3 \times 10^{15} \text{ cm } M_\odot^{1/2} L_{42}^{-1/2} R_{100}.$$  

We will approximate the suppression for $R > R_{\text{abl}}$ via $\dot{M}_{\text{abl}} \rightarrow \dot{M}_{\text{abl}} \exp (-R/R_{\text{abl}})^2$. Since the orbital distance $R_{d,15}$, the stellar mass $M_\star$, and the stellar radius $R_{100}$ are all time dependent, we find the total mass loss by integrating equation (2) or (4) numerically. For the AGN luminosity assumed, $L_{42} \approx 5 \times 10^{-2} L_{\text{Edd}}$ for a $3 \times 10^6 M_\odot$ BH, and the stellar envelope will be stripped from a star after $\sim 10\%$ of its main-sequence lifetime, or $\sim 10^7$ yr, if the star remains at $\sim 100$ AU from the BH throughout this time. Note that the star IRS 7 is known to be ablated (Serabyn et al. 1991); however, the inferred mass loss is 2 orders of magnitude higher than what would be expected from equation (3).

Proper-motion observations of GC stars have managed to pin down their orbital parameters, specifically, their eccentricity $e$ and pericenter distance $r_{\text{min}}$ (Schödel et al. 2003; Eisenhauer et al. 2005). The orbits are all highly eccentric, typically $e \approx 0.8–0.9$, while pericenter distances are of order $\sim 100–1000$ AU. Given these parameters, we can solve for the orbit $R(t)$ implicitly:

$$r = r_{\text{min}}(1 + e)$$

$$\frac{2\pi t}{\tau} = \psi - e \sin \psi,$$

$$\tan \left( \frac{\theta}{2} \right) = \tan \left( \frac{1 + e}{1 - e} \right) \tan \left( \frac{\psi}{2} \right),$$

where $\tau = 4\pi^2 a^3/(GM_{\text{AGN}})$ is the Keplerian orbital period, and the semimajor axis $a = r_{\text{min}}/(1 - e)$. In Table 1, we show the results for a 1 $M_\odot$ and a 2 $M_\odot$ giant undergoing mass loss for $\sim 10^6$ yr, assuming the observed orbital parameters.

The mass loss can be a significant amount of the star’s mass, but is still insufficient to boost the effective temperatures to sufficiently high values. This is because the orbits are highly eccentric and spend most of their time at large radii, far from pericenter,
r_{\text{min}}. We can compute the suppression factor compared to a purely circular orbit by considering the flux-weighted fraction of time an object spends close to pericenter in a single orbit,

$$f_{\text{supp}}(e) = \frac{r_{\text{min}}^2}{\tau} \int_0^{r_{\text{min}}} \frac{dt}{R^2(e, t)}$$

(it is acceptable to average over a single orbit, since the typical orbital period $\tau \sim 100$ yr is much less than the main-sequence lifetime; we are estimating the cumulative mass loss over many orbits). This is shown in Figure 7.

4. THE LACK OF GIANTS NEAR THE GALACTIC CENTER

Given the strong transformation in the atmosphere of old giant stars due to irradiation, it is worth exploring how the CO abundance correlates with distance from the GC. CO observations have been obtained for a dozen stars from 0.2 up to 3.6 pc from the GC (Sellgren et al. 1990). At smaller distances (<0.5 pc), spectra have been obtained by Genzel et al. (1997), Eckart et al. (1999), Figer et al. (2000), and Gezari et al. (2002) in the IR region to measure the CO band head absorption features. The observations show a clear decrease in the strength of the CO band at distances of about 0.5 pc from the GC. From our numerical experiments, we can measure the strength of the CO absorption as a function of distance from the GC. To do this, we have irradiated the stars with the same parameters as in §2 at different distances for the luminosity of the AGN at the GC today ($L_{\text{X}} = 10^{33}$ erg s$^{-1}$). As can be seen from Figure 3, the irradiated star with $f = f_0$ still contains CO.

Figure 8 shows our prediction (solid line) and the Sellgren et al. (1990), Genzel et al. (1997), Eckart et al. (1999), Figer et al. (2000), and Gezari et al. (2002) data. The CO observations of the S-cluster stars are shown as a diamond. For the S-cluster stars, all observations are consistent with zero detection, except for S0-17 and S0-18, where CO is marginally detected (Gezari et al. 2002).

To compute our predictions, we have chosen an average value of the eccentricity $e = 0.77$ from Table 1 and applied the corresponding suppression factor (0.2) from Figure 7 to the irradiated flux today. Although our model is not a perfect fit, the agreement is good, and the trend is reproduced, namely, a decrease in CO absorption band strength the closer the star is to the GC. This indicates that AGN irradiation is producing the right flux of photons to start CO destruction at a distance of ~1 pc. This implies that there might not be a lack of giants near the GC and that the only thing we might be seeing is a transformation of the spectrum of the star due to irradiation by the low-luminosity AGN.

5. DISCUSSION AND CONCLUSIONS

It has been argued in the literature (e.g., Ghez et al. 2003) that the observed spectra of the S-cluster stars are in agreement with standard spectra of type B8 or earlier, indicating that the stars are young, which is a puzzle, because at such distances the tidal force by the central black hole is far too great to be overcome by densities in normal molecular clouds. However, the effects of the radiation field due to Sgr A* on stellar atmospheres have hitherto not been taken into account. The upper layers of stars at the distance of the S-cluster will be strongly affected by this irradiation. We have therefore computed fully self-consistent stellar atmospheres where this irradiation is taken into account. The result is a substantial heating of the upper atmosphere. The heating of the upper layers of the atmosphere reduces the intensity of the CO bands, as well as all other molecular bands, thereby making even stars of quite late type look fairly like the observed S-cluster stars.

In particular, in the spectra from our model atmospheres of irradiated giant stars with $T_{\text{eff}} = 4000$ K, the intensity of the CO bands decreases when the distance to Sgr A is decreased, in qualitative agreement with the observations by Sellgren et al. (1990). This suggests that, contrary to previous claims, there is no dearth of old giants near the GC, as their molecular signatures have simply been wiped out by the radiation field from Sgr A*. However, some of the observed S-cluster stars have a strong He i line in their spectra. We have not been able to reproduce this line for irradiated low-mass stars for realistic values of the GC luminosity, suggesting that some other mechanism (perhaps recent star formation of massive star) is responsible for their presence.

Our illuminated atmospheric code is static. In fact, we have only been able to obtain converged models for values of $f < 100 f_0$. We have not been able with the present static code to predict the structure and spectrum of a star illuminated with $f > 100 f_0$. For doing this, a dynamic model is needed. It is not inconceivable that when dynamics effects are included and models are converged for $f > 100 f_0$, the spectra of these irradiated stars will look even more extreme than the models presented in this work. In particular, it will be interesting to investigate whether the He i line can be obtained at higher illuminations for dynamical models.

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Fig. 8.—Predicted strength of CO (solid line) as a function of distance from the GC for models irradiated by an AGN of luminosity $L_X = 10^{33}$ erg s$^{-1}$. Overplotted are CO measurements from Sellgren et al. (1990) and lack of detections at closer distances (<0.3 pc) by Genzel et al. (1997), Eckart et al. (1999), Figer et al. (2000), and Gezari et al. (2002).
