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

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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 ($L_X = 10^{33}$ erg 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 Sg 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: stars: winds - Galaxy: centre

1. INTRODUCTION

The fact that UV radiation and X-rays can alter the atmospheres of stars has been recognized for more than thirty years (Davidson & Ostriker 1973; Basko & Sunyaev 1973; Arons 1973; Basko et al. 1974; Fabian 1979). Irradiation by a source like 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, like 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 pre-cataclysmic variable). However, up to now, and 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 (~ 4000 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 ($L \approx 10^{39}$ erg 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 order one event per 10^4 yr or higher for solar-mass stars. Tidal disruption of a star by a SBH is expected to produce an extremely luminous event, $L \approx 10^{44}$ erg 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, and possible HeI (2.1 μm) 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 ~ 100 AU and an apocenter distance of ~ 1000 AU. The presence of the HeI line and the absence of CO point to S0-2 being young, with spectral class in the domain 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 S/N spectra of 17 S-cluster stars. For the brightest stars in this sample, spectra clearly show the presence of the HeI line at 2.1127μm. 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 possibility is that these stars are not young but old, and that their at-

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mospheres have been modified by some physical mechanism: 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 $10^{33} - 10^{44}$ erg s^{-1} integrated over the range $2 - 200$ keV (hereafter we denote the luminosity in this range by $L_{\rm X}$. In particular, we show how these old giants are affected by low-luminosity AGN ($L_{\rm X} \approx 10^{39}$erg s^{-1}) like the one that may have been present at the GC in the recent past, and also by the high luminosity ($L_{\rm X} \approx 10^{44}$ erg 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 ($L_{\rm X} < 10^{39}$ erg s^{-1}). Higher luminosities though, as the one from a tidally disrupted star are sufficient to heat up the stellar atmosphere above $15,000$ K, and therefore produce the HeI 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) 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 $f > 10^2$ erg 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 years, due to the high eccentricity of the S-cluster stars orbits, the amount of irradiation is most likely not sufficient to make the HeI line appear. On the other hand, stars on more circular orbits could potentially be sufficiently transformed to reproduce the spectral properties of the brightest S-cluster stars (including the HeI 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 $T_{\rm s}/T_i \sim (1 + F_x/F_i)^{(1/4)}$. At the microscopic level the X-rays photo-ionize He I, He II and O, C, Ne, N, Fe and its ions. Below 5000 K the main source of opacity is due to photodetachment of H^-, while above this temperature opacity is dominated by photo-ionization of oxygen and carbon. Basko & Sunyaev (1973) find that in their models the envelope develops a significant wind, although most of the energy is re-radiated. 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 Jorgensen et al. (1992), which 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 one time ionized atomic lines from the VALD data base 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 & Jorgensen 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 based on the same linelists. 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); Vaz & Nordlund (1985).

For reference, we first compute the spectra of non-irradiated oxygen-rich (C/O= 0.0, $T_{\rm eff}$ = 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 eq. 14 for the energy range $1{\rm eV} < E < 2\,{\rm keV}$ and their eq. 8 for $E > 2$ keV and 23 for $E < 1$ eV. The total flux for Sgr A*, assuming a mass of 3.7×10^6 $M_\odot$ is $L = 5.0 \times 10^{39} (f_{\rm EDD}/10^{-4})$ erg s^{-1} (Ghez et al. 2005). Although the Sazonov et al. (2004) spectral energy distribution is for typical QSO's we use it here as a good approximation to describe the AGN at the GC. Our results are not sensitive to moderate changes on the parameters that describe the spectral energy distribution of QSO's in Sazonov et al. (2004). For $f_{\rm EDD} = 10^{-4}$ 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 ($2 - 2.4\mu$) for the non-irradiated case is shown in Fig. 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 is 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 Brγ line at 2.1661μ. Note that there are no emission lines. It is also worth mentioning that there are no CO lines in the $2 - 2.3\mu$ range; they appear only at wavelengths beyond 2.3μ. Therefore, these strong bands would not be observed in the spectra of Ghez et al. (2003) or Eisenhauer et al. (2005). While the molecular bands are somewhat stronger than those observed in the faintest S-cluster stars, the spectrum of a non-irradiated 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)). Fig. 2 shows the non-irradiated spectrum for a carbon-rich star. Note the absence of CO lines be-

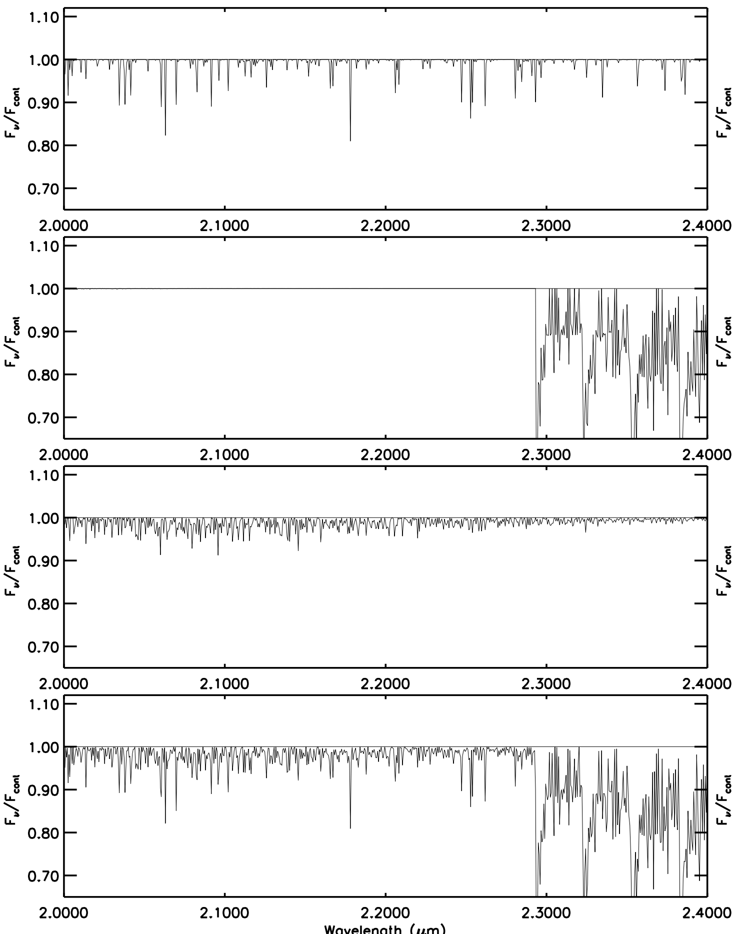

FIG. 1.— Theoretical IR spectrum of an oxygen-rich star at an effective temperature of 4000K. The upper panel shows the atomic lines, the second panel the CO lines, the third panel other molecules while the bottom panel shows the total spectrum. Note that the strong CO bands start at about 2.3μ, usually beyond the range observed by Ghez et al. (2003) and Eisenhauer et al. (2005). Note also the presence in the total spectrum of molecular-band absorption lines but also of the Brγ atomic line at 2.1661μ.

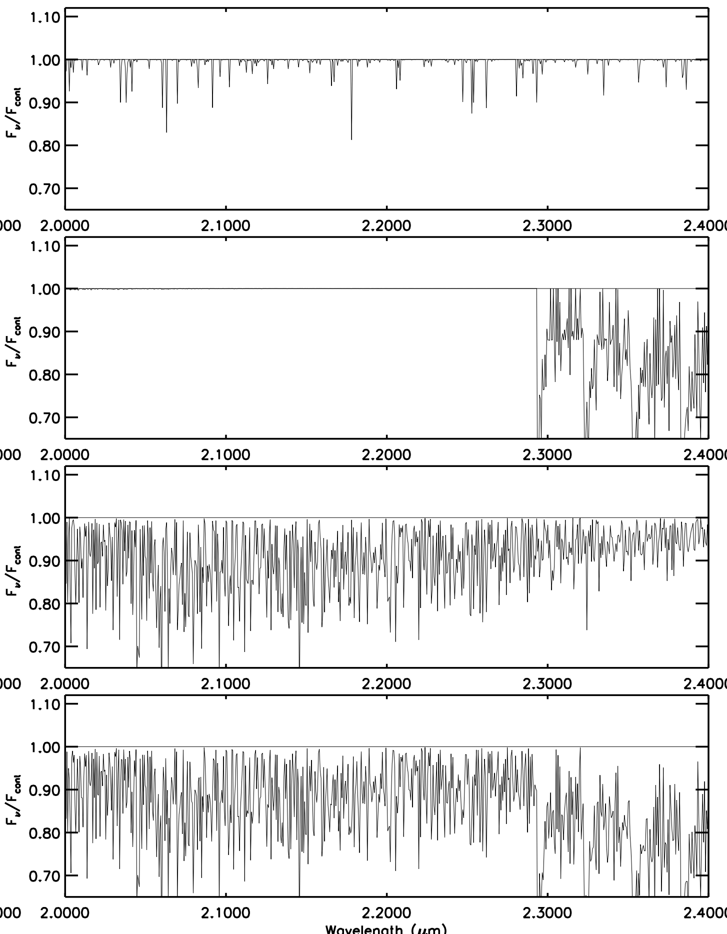

FIG. 2.— Same as Fig. 1 but for a carbon-rich giant. Note that CO lines are only present beyond 2.3μ, while the other molecules get considerably stronger than for an oxygen-rich star.

low 2.3μ (they are very strong CO bands beyond this wavelength) and the increase in the strength of the other molecular bands. Clearly, the non-irradiated spectrum of a C-rich giant does not resemble at all any of the observed S-cluster stars.

We then irradiate the star as described above, assuming different incident fluxes. Fig. 3 assumes an orbit averaged flux:

$$f_o = 2\left(\frac{L}{10^{33}\mathrm{erg\,s^{-1}}}\right)\left(\frac{f_{\rm supp}}{0.6}\right)\left(\frac{r_{\rm min}}{100\,\mathrm{A.U.}}\right)\frac{\mathrm{erg}}{\mathrm{s\,cm^2}} \quad (1)$$

where $r_{\rm min}$ is the pericenter distance. See Eq. 6 and Fig. 7 for a definition of $f_{\rm sup}$. On the other hand, Fig. 4 assumes a flux of $f = 10^2 f_o$, corresponding to a star illuminated by Sg A^* during a more active state when $L \approx 10^{35}\mathrm{ergs}^{-1}$, 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 larger illumination fluxes that $f = 10^2 f_o$. For this dynamic models are required, which we are currently constructing. However, even for $f = 10^2 f_o$ the transformation of the spectrum is significant.

The first thing to note from Fig. 3 is the decrease in the strength of the molecular lines even for $f = f_o$. Note also the reduction of the CO band intensity. If we examine the spectrum of the star for $f = 10^2 f_o$, (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 $2.1661\,\mu$ is now in emission. At this small distance, irradiation results in a rise in the temperature of the atmosphere at $\tau_{\rm ROSS} = 10^{-4.9}$ from 2500 K to 8000 K. However, the HeI line at $2.11\,\mu$ 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 (5×10^{-4} to 5×10^{-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 Fig. 3, which is equivalent to a star irradiated at a distance of a few hundred AU but with a luminosity of $L_{\rm X} \sim 10^{33}$ erg s^{-1} the similarity with the faintest stars of the Eisenhauer et al. (2005) sample is striking. In this case, the HeI line is absent and the deepest absorption feature in the spectrum is

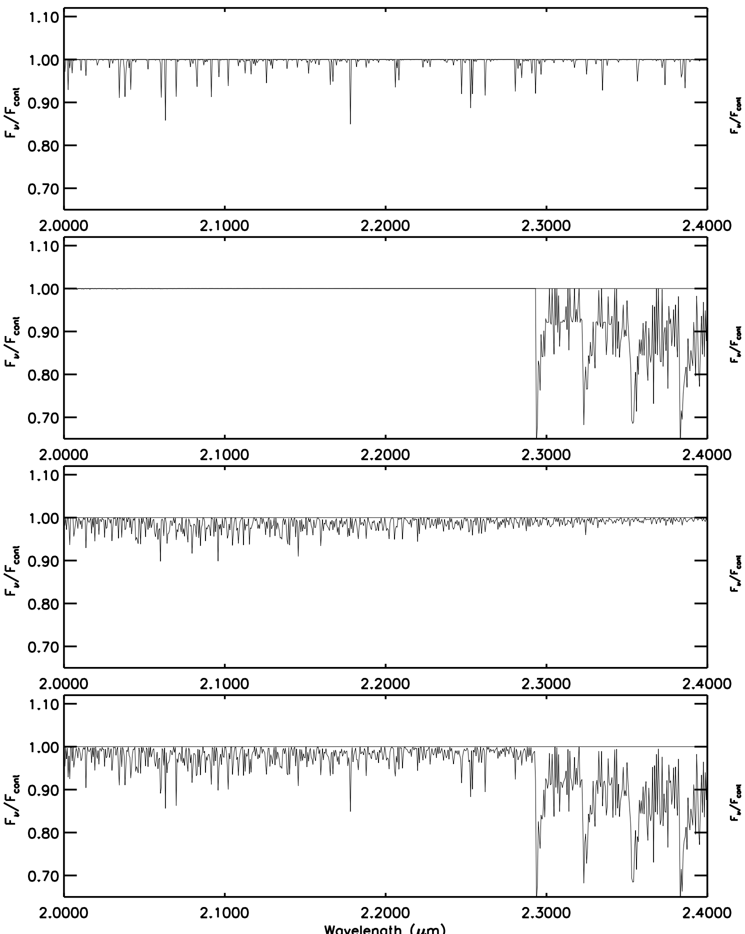

FIG. 3.— IR spectrum of an irradiated oxygen-rich star illuminated with a flux $f = f_o$. The upper panel shows the atomic lines, the second panel the CO lines, the third panel other molecules while the bottom panel shows the total spectrum. Note the decrease in the strength of the molecular lines with respect to the non-irradiated spectrum of Fig. 1.

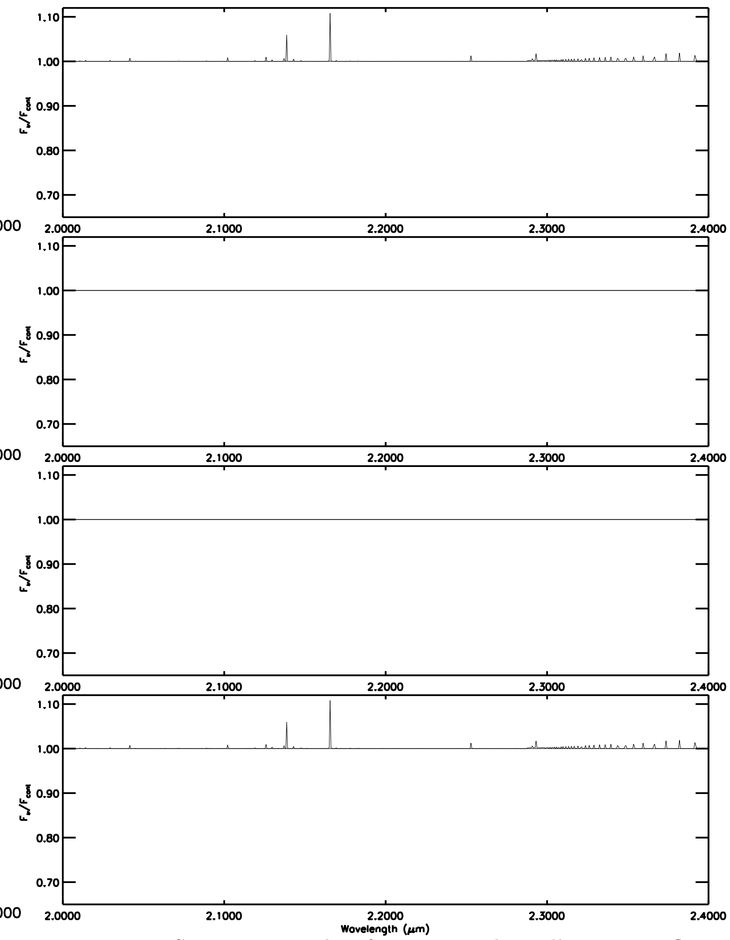

FIG. 4.— Same as Fig. 3 but for a star with an illumination flux $f = 100f_o$. Note the extreme transformation of the spectrum with now only atomic lines in emission and no molecules, including CO.

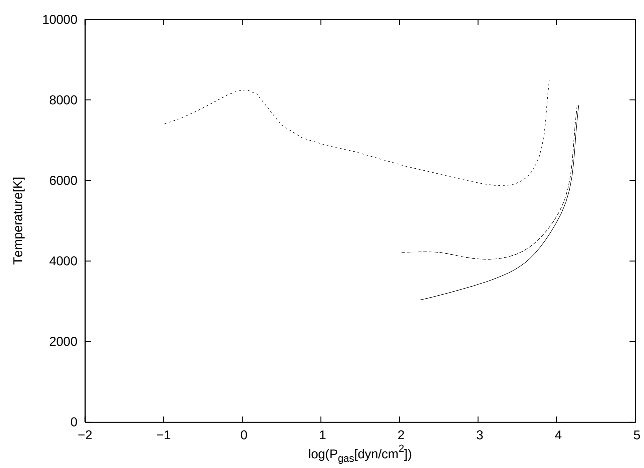

FIG. 5.— Plot of the $T - P_{\rm gas}$ structure of the relevant model atmospheres: solid line is for $f = 0$, dashed line is for $f = f_o$ and dotted line is for $f = 100f_o$. Note the inversion temperature layer that takes places at illumination fluxes of $f = 100f_o$

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 2000K, molecules will form immediately on a time scale of seconds). However, the presence of illumination will stop convection on the atmosphere. It takes of the order of a few hundred years for convection to be restored and therefore the temperature in the outer layers to decrease enough for molecules to be allow to reform. This argument also assures that the time-scale of molecule formation is longer than the rotation time-scale 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 Fig. 3.

Figure 5 shows the temperature versus gas pressure model structure for a oxygen-rich giant for $f = 0, f_o$ and $10^2 f_o$. In the moderately irradiated model $f = f_o$ from the GC (as well as in the non-irradiated model), the upper layers are relatively dense ($P_{\rm gas} \approx 100$ dyn/cm^2). Therefore the absorption of radiation from the SBH at the GC is substantial already 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 $f = f_o$. For $f = 10^2 f_o$ the radiation is strong enough that the atmosphere is

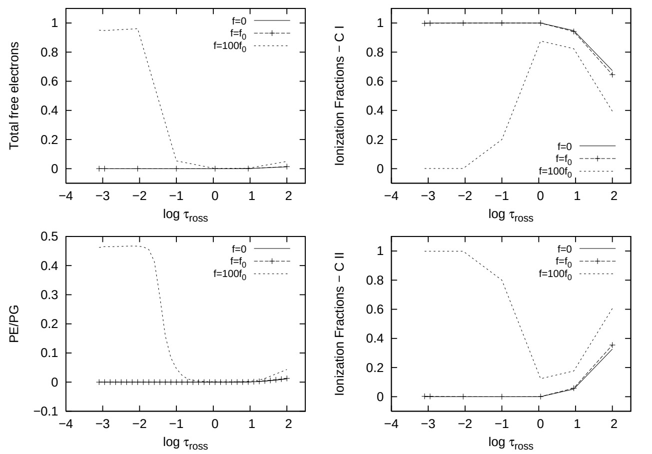

FIG. 6.— The plot shows the value of the ionization fractions of CI and CII (right panels) and electron pressure over gas pressure (bottom-left panel) and total density of free electrons (upper left panel) for non-irradiated and irradiated models.

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 (CI) and one time ionized (CII) carbon (the two right panels) for the three models in Fig. 5. Other atoms, including H, N, O, Al, Si, S, Ca, and Ni, behave qualitatively similarly (whereas Ca, Mg, Cr and Fe are substantially double ionized in the top-layers, and He is neutral throughout the atmosphere). The main contributer 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 $\log \tau_{\rm ROSS} \approx 0$ to -2. This is the region of temperature rise in the strongly irradiated model ($\log {\rm P_{gas}}$ from ≈ 3 to 0). From $\log \tau_{\rm ROSS} = -2$ and outward hydrogen is fully ionized, and the electron density and pressure therefore now again decreases outward. As a consequence the opacity decreases in the outermost layers, and the energy deposition due to external illumination also decreases outwards from $\log P_{\rm gas} = 0$ onwards. The temperature therefore decreases toward the surface from this point onwards, just like in a normal photospheric model. This feature is not seen in any chromospheric model heated from below. It is particular 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 the previous section, up to $\sim 0.5\% L_{\rm Edd}$. 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 $T_{\rm eff} \approx 15\,000$ K (which is high enough to produce the observed HeI line), then these modified stars could explained the observed S-cluster stars, though stars with higher effective temperatures will have lifetimes which 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 than 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.

Regardless, 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 radius. 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 $T_{\rm eff}$ of the stripped star, and its new radius R_*, assuming $L = 4\pi R_*^2 \sigma T_{\rm eff}^4$=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 AGN. 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:

$$\dot{M}_{\rm thermal} = 5.0 \times 10^{-6}\,{\rm M_\odot\,yr^{-1}} L_{42}^{0.9} R_{d,15}^{-1.8} R_{*,100}^{2} \quad (2)$$

reproduces their results very well, as well as the previous analytic results of Basko et al. (1977). Here $L_{42} \equiv L/(10^{42} {\rm erg\,s^{-1}})$ is the AGN luminosity, $R_{d,18} \equiv R_d/10^{18}$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

$$\dot{M}_{\rm abl} \approx 3.8 \times 10^{-6}\,{\rm M_\odot\,yr^{-1}} L_{42} R_{d,15}^{-2} M_*^{-1/2} R_{*,100}^{5/2} \quad (3)$$

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

$$R_{\rm abl} = 6.3 \times 10^{15}\ {\rm cm}\ M_*^{1/2} L_{42}^{1/2} R_{100}. \quad (4)$$

We will approximate the suppression for $R > R_{\rm abl}$ via $\dot{M}_{\rm abl} \to \dot{M}_{\rm abl} \exp(-R/R_{\rm abl})^2$. Since the orbital distance $R_{d,15}$, the stellar mass M_* and the stellar radius $R_{*,100}$ are all time-dependent, we find the total mass loss by integrating equations (2) or (4) numerically. For the AGN luminosity assumed, $L_{42} \sim 5 \times 10^{-3} L_{\rm Edd}$ for a $3 \times 10^6 M_\odot$ SBH, the stellar envelope will be stripped from a star after $\sim 10\%$ of its main sequence lifetime, or $\sim 10^5$ years, if the star remains at ~ 100 A.U. from the SBH throughout this time.

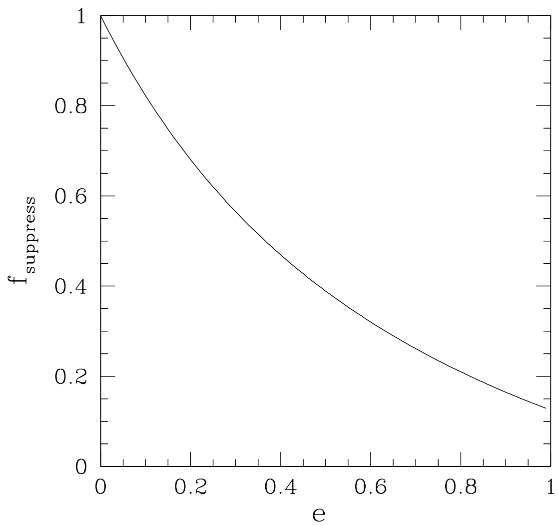

FIG. 7.— The flux weighted fraction of time an object spends close to pericenter, as given by equation (6), as a function of the eccentricity e. This gives the relative reduction in flux compared to a circular orbit at pericenter distance.

Proper motion observations of GC stars have managed to pin down their orbital parameters: specifically, their eccentricity e and pericenter distance $r_{\rm min}$ (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 $\sim 100 - 1000$ A.U. Given these parameters, we can solve for the orbit $R(t)$ implicitly:

$$r = \frac{r_{\rm min}(1+e)}{(1+e\cos\theta)} \tag{5}$$

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

$$\tan\left(\frac{\theta}{2}\right) = \tan\left[\left(\frac{1+e}{1-e}\right)^{1/2}\tan\frac{\psi}{2}\right]$$

where $\tau = \left[4\pi^2 a^3/(GM_{\rm AGN})\right]^{1/2}$ is the Keplerian orbital period, and the semi-major axis $a = r_{\rm min}/(1-e)$. In Table 1, we show the results for a $1M_\odot$ and $2M_\odot$ giant undergoing mass loss for $\sim 10^6$ years, 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 $r_{\rm min}$. 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:

$$f_{\rm supp}(e) = \frac{r^2_{\rm min}}{\tau}\int_0^\tau \frac{dt}{R^2(e,t)}. \tag{6}$$

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

TABLE 1
MASS LOSS AND STELLAR EFFECTIVE TEMPERATURES FOR MEASURED ORBITS. THE ORBITAL PARAMETERS ARE FROM THE FITS OF EISENHAUER ET AL (2005). WE ASSUME THE AGN SHINES WITH A LUMINOSITY $L = 10^{43}\,{\rm erg\,s^{-1}}$ FOR $\sim 10^6$YRS. THE FIRST SET OF COLUMNS IS FOR A $1M_\odot$ STAR WITH AN INITIAL $T_{\rm eff} = 3000$K, $R_{*,100} = 1$, THE SECOND SET OF COLUMNS IS FOR A $2M_\odot$ STAR WITH AN INITIAL $T_{\rm eff} = 4000$K, $R_{*,100} = 1.23$.

	$r_{\rm min}$/AU	e	$\Delta M/{\rm M}_\odot$	$T_{\rm eff}$/K	$\Delta M/{\rm M}_\odot$	$T_{\rm eff}$/K
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

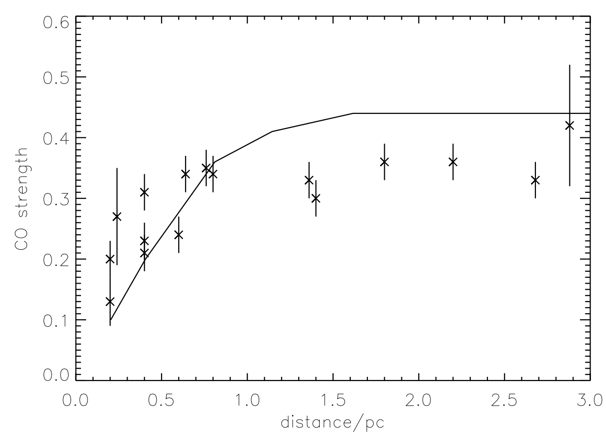

FIG. 8.— Predicted strength of CO (solid line) as a function of distance from the GC for models irradiated by an AGN of luminosity $L_{\rm X} = 10^{33}$ erg s^{-1}. Overplotted are CO measurements from Sellgren et al. (1990).

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 pc up to 3.6 pc from the GC (Sellgren et al. 1990). They 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 star with the same parameters as in §2 at different distances for the luminosity of the AGN at the GC today ($L_{\rm X} = 10^{33}$ erg s^{-1}). As can be seen from Fig. 3, the irradiated star with $f = f_o$ still contains CO.

Fig. 8 shows our prediction (solid line) and the Sellgren et al. (1990) data. To compute our predictions we have chosen an average value of the eccentricity $e = 0.77$ from Table 1 and applied the corresponding suppression (0.2) factor from Fig. 7 to the irradiated flux today. Although our model is not a perfect fit, the agreement is good and the general 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 $\sim$ 1pc. 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 BH is far to great to be overcome by densities in normal molecular clouds. However, effects of the radiation field due to Sg A^* on stellar atmospheres has 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 take into account. The result is a substantial heating of the upper atmosphere. The heating of the upper layers of the atmosphere reduce the intensity of the CO bands as well as all other molecular bands, hereby making even stars of quite late type look fairly much like the observed S-cluster stars.

In particular, in the spectra from our model atmospheres of irradiated giant stars with $T_{\rm eff} \approx 4000$K, the intensity of the CO bands is decreasing 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 galactic center; their molecular signatures have simply been wiped out by the radiation field from SgA^*. However, some of the observed S-cluster stars have a strong HeI 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 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 $f < 100 f_o$. We have not been able with the present static code to predict the structure and spectrum of a star illuminated with $f > 100 f_o$. For doing this a dynamic model is needed. It is not inconceivable that when dynamics effects are included and models are converged for $f > 100 f_o$, 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 if the HeI line can be obtained at higher illuminations for dynamical models.

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REFERENCES

Alencar, S. H. P., Vaz, L. P. R., & Nordlund, Å. 1999, A&A, 346, 556
Alexander, T. 2005, Phys. Rep., 419, 65
Alexander, T., & Morris, M. 2003, ApJ, 590, L25
Arons, J. 1973, ApJ, 184, 539
Barman, T. S., Hauschildt, P. H., & Allard, F. 2004, ApJ, 614, 338
Basko, M. M., & Sunyaev, R. A. 1973, Ap&SS, 23, 71
Basko, M. M., Sunyaev, R. A., Hatchett, S., & McCray, R. 1977, ApJ, 215, 276
Basko, M. M., Sunyaev, R. A., & Titarchuk, L. G. 1974, A&A, 31, 249
Chiu, W. A., & Draine, B. T. 1998, ArXiv Astrophysics e-prints
Davidson, K., & Ostriker, J. P. 1973, ApJ, 179, 585
Davies, M. B., & King, A. 2005, ApJL, 624, L25
Edwards, A. C. 1980, MNRAS, 190, 757
Eisenhauer et al., F. 2005, ApJ, 628, 246
Fabian, A. C. 1979, Royal Society of London Proceedings Series A, 366, 449
Genzel, R., Schödel, R., Ott, T., Eisenhauer, F., Hofmann, R., Lehnert, M., Eckart, A., Alexander, T., Sternberg, A., Lenzen, R., Clénet, Y., Lacombe, F., Rouan, D., Renzini, A., & Tacconi-Garman, L. E. 2003, ApJ, 594, 812
Ghez, A. M., Duchêne, G., Matthews, K., Hornstein, S. D., Tanner, A., Larkin, J., Morris, M., Becklin, E. E., Salim, S., Kremenek, T., Thompson, D., Soifer, B. T., Neugebauer, G., & McLean, I. 2003, ApJL, 586, L127
Ghez, A. M., Salim, S., Hornstein, S. D., Tanner, A., Lu, J. R., Morris, M., Becklin, E. E., & Duchêne, G. 2005, ApJ, 620, 744
Goodman, J., & Paczynski, B. 2005, ArXiv Astrophysics e-prints
Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, A. 1975, A&A, 42, 407
Hansen, B. M. S., & Milosavljević, M. 2003, ApJ, 593, L77
Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, 107, 281
Helling, C., & Jorgensen, U. G. 1998, A&A, 337, 477
Jimenez, R., MacDonald, J., Dunlop, J. S., Padoan, P., & Peacock, J. A. 2004, MNRAS, 349, 240
Jørgensen, U. G. 2003, in ASP Conf. Ser. 288: Stellar Atmosphere Modeling, 303
Jørgensen, U. G. 2005, in ASP Conf. Ser. 336: Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, 269
Jorgensen, U. G., Johnson, H. R., & Nordlund, A. 1992, A&A, 261, 263
Komossa, S. 2002, in Lighthouses of the Universe: The Most Luminous Celestial Objects and Their Use for Cosmology Proceedings of the MPA/ESO/, p. 436, 436
Merritt, D., & Szell, A. 2005, ArXiv Astrophysics e-prints
Nordlund, A., & Vaz, L. P. R. 1990, A&A, 228, 231
Phinney, E. S. 1989, in NATO ASIC Proc. 290: Theory of Accretion Disks, 457
Revnivtsev, M. G., Churazov, E. M., Sazonov, S. Y., Sunyaev, R. A., Lutovinov, A. A., Gilfanov, M. R., Vikhlinin, A. A., Shtykovsky, P. E., & Pavlinsky, M. N. 2004, A&A, 425, L49
Sazonov, S. Y., Ostriker, J. P., & Sunyaev, R. A. 2004, MNRAS, 347, 144
Schödel, R., Ott, T., Genzel, R., Eckart, A., Mouawad, N., & Alexander, T. 2003, ApJ, 596, 1015
Sellgren, K., McGinn, M. T., Becklin, E. E., & Hall, D. N. 1990, ApJ, 359, 112
Vaz, L. P. R., & Nordlund, A. 1985, A&A, 147, 281
Voit, G. M., & Shull, J. M. 1988, ApJ, 331, 197
Wang, J., & Merritt, D. 2004, ApJ, 600, 149