Black Holes from Stars to Galaxies – Across the Range of Masses
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The capture of main sequence stars and giant stars by a massive black hole

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Abstract. Since the mass-radius relation is quite different for a main sequence (MS) star and a giant (G) star, we find that the radiation efficiencies in the star capture processes by a black hole (BH) are also very different. This may provide a useful way to distinguish the capture of MS and G stars. Comparing with observations of the very high energy (VHE) gamma-ray emissions, we argue the event that triggers the gamma-ray emission in the energy range 4–40 TeV should be a G star capture. On the other hand, the capture of MS stars by the massive BH is required when the measured spectrum of VHE gamma-rays extends from 10^9 to 10^{15} eV.

Keywords. Galaxy: center – galaxies: active – galaxies: jets – galaxies: gamma rays – accretion, accretion disks – black holes

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When a star with a given mass of M_* and radius of R_* passes by a BH with a mass of M_{bh}, the star could be tidally disrupted and captured. This picture is described in the left panel of Fig.1. In the phase 2 (the fallback stage), a fraction of the material in the disrupted stars remains gravitationally bound to the BH at the pericenter. The timescale and the accretion rate (Phinney 1989) for the debris to return to the pericenter are $t_{min} \approx 0.11 m_*^{-1} r_*^{3/2} M_6^{1/2}\ yr$ and $\dot{M} = 1.29 f_{0.3} m_*^2 r_*^{-3/2} M_6^{-1/2} (\frac{t}{t_{min}})^{-5/3} M_\odot\, yr^{-1}$, respectively, where $m_* = M_*/M_\odot$, $M_6 = M_{bh}/10^6 M_\odot$, $r_* = R_*/R_\odot$, f is the fraction of the stellar material falling back to the periastron, and $f_{0.3} = f/0.3$. Assuming that the fallback material radiates the energy release promptly, the radiation efficiency ϵ (Li *et al.* 2002) is $\epsilon \approx 5.38 \times 10^{-3} r_*^{-1} m_*^{1/3} M_6^{2/3}$. Immediately, the total kinetic energy of the jet can be estimated as (Lu *et al.* 2006), $E_{jtot}^{proton} = \int_{t_{peak}}^{t_{crit}} q_j \epsilon \dot{M} c^2 dt$, where q_j is the efficiency that transfers the accretion energy into the jet power, $t_{peak} \sim 0.157 m_*^{-1} r_*^{3/2} M_6^{1/2}\ yr$ and $t_{crit} \sim 1.67 \times 10^2 f_{0.3}^{3/5} m_*^{2/5} M_6^{3/5}\ yr$ are the time since the radiation reaches the peak luminosity and the time that the jet exists, respectively. The viscous accreting timescale (Lu *et al.* 2006) is $t_{acc} \approx 2.08 \times 10^2 (h/r)_{-2}^{-2} \alpha_{0.1}^{-1} m_*^{-1/2} r_*^{3/2}\ yr$, where $(h/r)_{-2} = (h/r)/10^{-2}$ and $\alpha_{0.1} = \alpha/0.1$. For typical MS stars with masses $0.08 M_\odot \leqslant M_* \leqslant 1 M_\odot$, the radius and mass could be related by $r_* = m_*$. And for G stars, the radius-mass relation (Joss *et al.* 1987) is $r_* \approx \frac{3.7\times10^3 m_*^4}{1+m_*^3+1.75 m_*^4}$, where $m_* \equiv M_c/M_\odot$ for a giant star, M_c is a mass of its core, and $0.17 M_\odot \lesssim M_c \lesssim 0.45 M_\odot$.

With these mass-radius relations of stars and $q_j = 0.1$, the radiation efficiency and the total injection energy of protons captured by the BH with mass of $10^6 M_\odot$, $10^7 M_\odot$ and $10^8 M_\odot$ are plotted in Fig. 2. Paying attention to the injection energy required by the hadronic model(Aharonian & Neronov 2005) to produce the VHE gamma-rays (Lu *et al.* 2006), one can find that the G star capture by the BH is favored for the

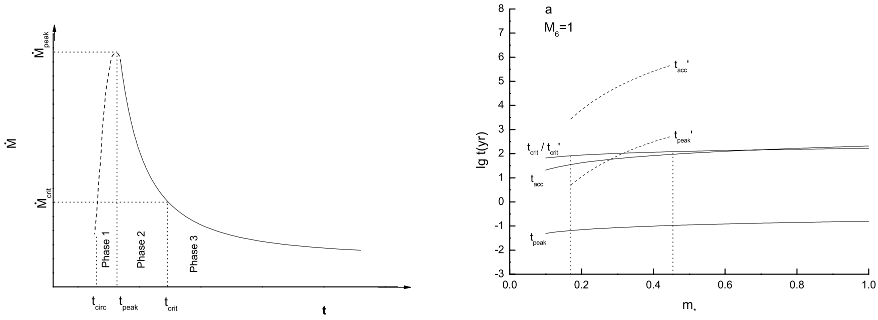

Figure 1. The left panel shows the behavior of the accretion rate versus time ($\dot{M} - t$) when a black hole captures a star, where $t_{circ} = 2t_{min}$. The right panel shows the various timescales involved in the capture processes change as function of the stellar mass: t_{acc}, t_{peak} and t_{crit} are the capture of the MS star, while those primes are for the capture of the G star.

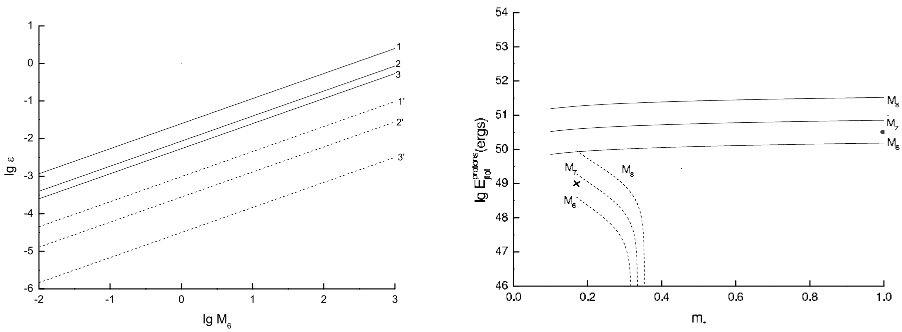

Figure 2. Lines of 1, 2, 3 in the left panel and the light lines in the right panel correspond to the capture of the MS stars, respectively. While lines of 1', 2', 3' in the left panel and the black lines in the right panel are for the capture of G stars. In the right panel, the cross represents the capture of a G star fit to the injection energy of protons required by the hadronic model with the parameters of $M_6 = 3$, $\epsilon = 2.17 \times 10^{-3}$ and $m_* = 0.17$; while the filled dot stands for the capture of a MS star fitting with $M_6 = 3$, $\epsilon = 1.12 \times 10^{-2}$ and $m_* = 1$.

gamma-rays emitted in the energy range of 4-40 TeV, and the MS case is reliable for the VHE gamma-rays with the radiated energy extended to 10^{15} TeV.

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