Quasars: Feeding the Monster

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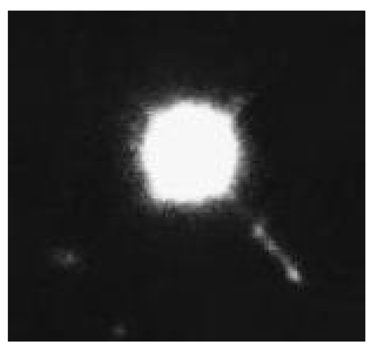
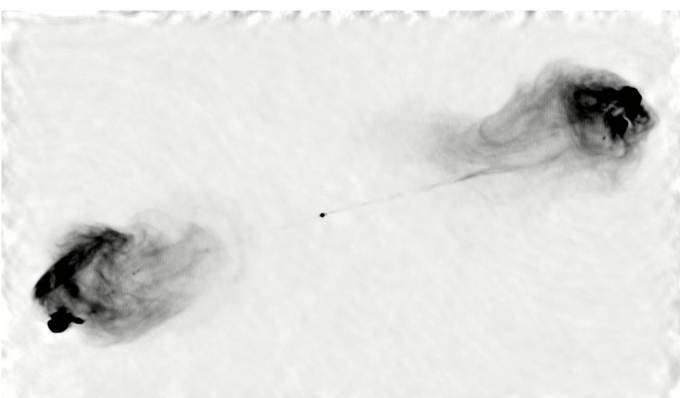
Quasi-Stellar Objects and quasars, their radio-loud subset, shine by accretion of several solar masses per year onto black holes of up to several billion solar masses, probably *via* a disk, whose optically luminous regions extend to ~ 0.1 light-years from the hole. These outer regions are partially selfgravitating, perhaps more so than the young circumstellar disks from which planets form. We argue therefore that quasar disks may form "stars" of up to $10^5 - 10^6$ solar masses. These stars may be sensed by future space-based gravitational-wave experiments.

1 Introduction

The first sentence above has long been supported by strong theoretical arguments, but only recently proved. (*i*) Since both gravity and radiation pressure yield inverse-square forces, a minimum ("Eddington") mass is required to bind hydrogen plasma to a luminous source:

$$M_{\rm Edd} = \frac{L\sigma_T}{4\pi G m_{\rm p} c} \approx 10^8 \frac{L}{10^{46}\,{\rm erg\,s^{-1}}} M_\odot, \tag{1}$$

where $M_\odot = 2\times 10^{33}\,{\rm g}$ = solar mass. (*ii*) Fluctuations indicate sizes $\lesssim 1$ light-month, too small for stellar clusters but larger than the Schwarzschild radius $r_{\rm s} \equiv 2GM/c^2 \approx 10^2 (M_{\rm bh}/10^8 M_\odot)$ light-sec. (*iii*) Thin-disk accretion onto a maximally rotating black hole—a likely result of angular momentum conservation—has maximum radiative efficiency $\varepsilon \equiv L/\dot M_{\rm bh} c^2 \approx 0.3$, as compared to $\varepsilon \lesssim 0.007$ for fusion. The luminosities are stupendous: placed at the center of the Milky Way, a bright quasar would rival the full moon (save for interstellar dust).

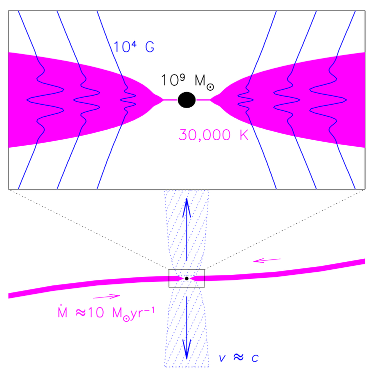
Left: Optical image of first known quasar, 3C273 [Credit: NOAO/AURA/NSF]. Note jet at 5 o'clock. Right: Jets of Cygnus A, probably an optically obscured quasar, in 6-cm radio waves [7]. Tip-to-tip length of jets $\approx 5\times 10^5\,{\rm lt-yr}$ in projection.

Even so, fueling rates $\dot M = L/\varepsilon c^2 \approx 1.75\,(10\varepsilon)^{-1}(L/10^{46}\,{\rm erg\,s^{-1}})\,M_\odot\,{\rm yr}^{-1}$ suggest very dense environments such as galactic nuclei, as is now confirmed by space-based observations (*e.g.* [3]). Yet it is a difficult to understand how interstellar gas funnels from galactic scales $\gtrsim 10^3\,{\rm lt-yr}$ down to the Schwarzschild radius $r_{\rm s} \sim 10^{-4}\,{\rm lt-yr}$ at such high rates. This problem has been the main theme of our own recent research on QSOs.

Mass that is accreted but not radiated adds to the mass of the black hole. Thus the observed density of QSO light has been used to predict average "relic" black-hole masses per bright galaxy $\approx 3\times 10^7 (10\varepsilon)^{-1} M_\odot$ [10, 2]. In the past decade, stellar velocities in nearby inactive galactic nuclei, including the Milky Way, have revealed dark masses $\sim 10^6 - 10^{10}\,M_\odot$ on the smallest measurable scales ($\lesssim 10^6 r_{\rm s}$). The inferred cosmological density of these black holes agrees very well with the earlier predictions if $\bar\varepsilon \approx 0.1$, while the distribution of masses indicates that bright QSOs have nearly the maximum luminosity:mass ratio (1) [11, 3]. **These recent successes place the black-hole model of QSOs beyond reasonable doubt, at least in broad outline.**

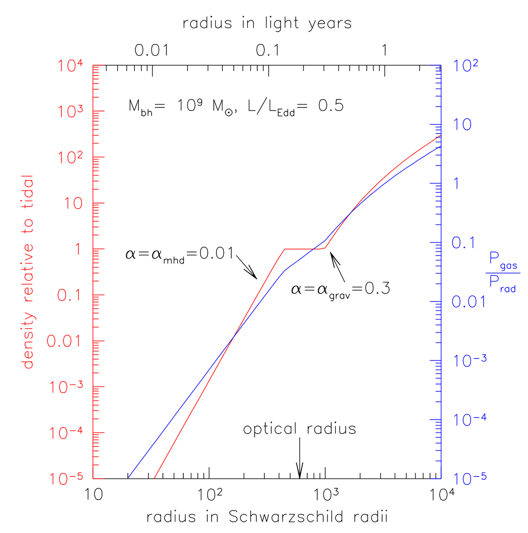
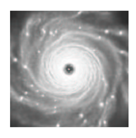
2 Selfgravity of QSO accretion disks

Disk accretion is strongly favored by angular-momentum considerations and by its high radiative efficiency, although the luminous parts of QSO disks have angular sizes too small to be resolved ($\theta \sim 10^{-11}\,{\rm rad}$).



Theorist's cartoon of a bright quasar, seen in closeup (above) and on somewhat larger scales (below). Disk thickness is constant except near inner edge. Magnetic field (blue) probably mediates orbital dissipation and may also launch a relativistic axial outflow ("jet"). A large-scale warp in the disk is possible.

The basic structure of a QSO accretion disk is largely fixed by energy and momentum conservation given $M_{\rm bh}$ and $\dot M = L/\varepsilon c^2$, where L is the integrated luminosity of the disk. Within $10^3 - 10^4 r_{\rm s}$, radiation pressure exceeds gas pressure. The orbital dissipation rate per unit area is $(3/4\pi) G M \dot M_{\rm bh} r^{-3}$, and the half-thickness is constant, $H \approx (\dot M c^2/L_{\rm Edd}) r_{\rm s}$, except where $r \sim r_{\rm s}$. Here $L_{\rm Edd}$ is the maximum disk luminosity, which is computed from eq. (1) by setting $M_{\rm Edd} = M_{\rm bh}$. However, the disk density (ρ) and hence selfgravity depend also upon the poorly understood rate of orbital dissipation *per unit mass*. The latter is parametrized by a dimensionless coefficient α such that the inflow speed $v_r = -(3\alpha/2)\Omega H^2/r$, where $\Omega = (GM_{\rm bh}/r^3)^{1/2}$ is the orbital angular velocity. It is believed on general grounds that $\alpha < 1$. 3D magnetohydrodynamic simulations find $\alpha_{\rm MHD} \approx 10^{-2}$ [1], rising to $\alpha \lesssim 0.3$ in a marginally self-gravitating state [4].

Left: Selfgravity $2\pi G\rho/\Omega^2$ (red) in a bright QSO disk. "Optical radius" is minimum disk size for incoherent emission of observed luminosity at $\lambda \sim 0.5\,\mu{\rm m}$ and $T_{\rm rad} \sim 10^4\,{\rm K}$ [5].
Right: 3D-hydro simulation of a marginally selfgravitating but gas-pressure-dominated disk [8]. Note fragments.

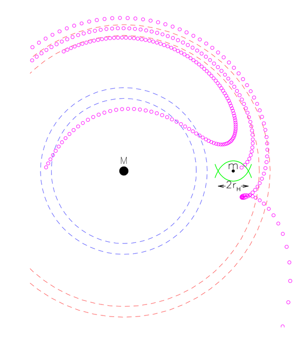
The "shelf" in the red curve marks a region where α adjusts itself so as to maintain the disk at marginal gravitational instability, up to $\alpha_{\rm max} = 0.3$, whereafter the the disk is likely to break up into selfgravitating lumps. The shelf moves to larger r but smaller $r/r_{\rm s}$ with increasing $M_{\rm bh}$ at fixed $L/L_{\rm Edd}$. Note radiation pressure dominates throughout the region of interest (blue curve). **Even with extreme nonstandard assumptions, it does not seem possible that a predominantly gaseous disk extends with constant accretion rate beyond a few thousand Schwarzschild radii in a bright QSO[5, 9].**

3 Formation and Detection of Supermassive stars

A seed mass $m(0) \gtrsim \rho H^3$ captures much of the disk within an annulus $|r - r_m| \lesssim r(m/3M_{\rm bh})^{1/3} \equiv \Delta r_H$, the **Hill radius**, thereby reaching ultimate ("isolation") mass

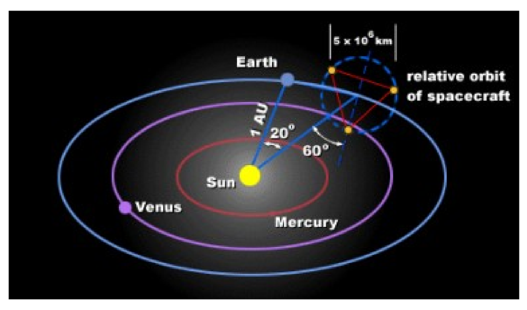
$$M_{\rm iso} \sim M_{\rm disk}^{3/2} \Big/ M_{\rm bh}^{1/2}. \tag{2}$$

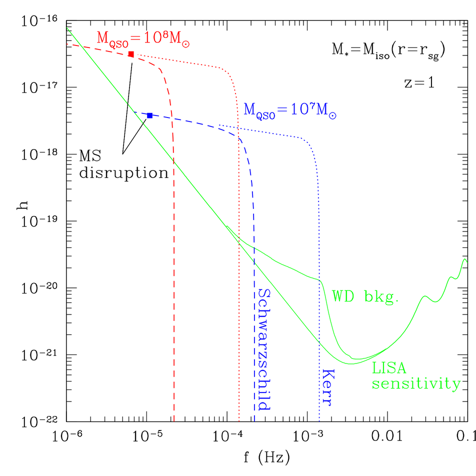
This argument, when applied to the primordial solar nebula, explains the mass of Jupiter. In bright QSOs, at the radius of marginal selfgravity ($r_{\rm s.g.}$), $M_{\rm disk} \sim 10^{-2} M_{\rm bh}$ and $M_{\rm iso} \sim 10^5 - 10^6\,M_\odot$.



Restricted planar 3-body problem in frame co-orbiting with mass m. Test particles on initially circular orbits within the blue and red dashed lanes ($1.72 \lesssim |r - r_m|/\Delta r_H \lesssim 2.43$) penetrate the Hill "sphere" (green) on first passage. Those between these lanes execute "horseshoe" orbits but some are captured later after dissipation. These trajectories neglect pressure, which is justified, except at shocks, when $\Delta r_H \gg H$.

It is unclear whether so massive a "star" would promptly collapse, promptly explode, or live out its main-sequence lifetime ($\sim 10^6\,{\rm yr}$). In all three cases, it would be hard to detect optically. But it would drift inward with the accretion of the disk, and eventually emit powerful, low-frequency gravitational waves. Hence the best hope for detection lies with future space-based gravitational-wave detectors such as LISA, a joint NASA-ESA mission scheduled for $\gtrsim 2011$.





Left: Laser Interferometer Space Antenna concept. 3 free-flying spacecraft in Earth orbit; gravitational wave strain $h = \Delta\ell/\ell$ is sensed via laser ranging of distance ℓ between spacecraft.
Right: Gravitational waves from inspiral of mass $M_{\rm iso}$ formed at radius of marginal selfgravity. A source at redshift $z = 1$ is assumed in a standard cosmology ($\Omega_\Lambda = 0.7$, $\Omega_{\rm matter} = 0.3$). Signal evolves toward the right along dashed (dotted) tracks for nonrotating (maximally rotating) holes, respectively. Green lines mark detection threshold of one-year integration with (upper) and without (lower) estimated interference from local white-dwarf binaries. Squares mark point of tidal disruption if star is on main-sequence [6].

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