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THE BLACK FLASH MODEL OF QSOs

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Summary

A model for QSOs and the nuclei of Seyfert Galaxies is proposed in which mass lost from stars in a galactic nucleus repeatedly builds to a critical density and then collapses to the center where it accretes onto a massive black hole ($\sim 10^8\ M_\odot$), emitting great luminosity. This model describes a means of starting with an ordinary nucleus and developing conditions found in QSOs. By invoking intermittent flashes we overcome a difficulty previously encountered in similar models in which plausible sources of mass in reasonable galactic nuclei fail by a factor $\sim 10^{-2}$ of fueling a black hole at QSO luminosities.

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After more than a decade of study, there is no widely accepted theory of the energy source of quasars. If we assume that they are at cosmological distances, the QSOs pour forth a luminosity of 10^{12} to 10^{14} suns. The nuclei of Seyfert galaxies, for which there is no distance controversy, deliver a power of 10^{10} to 10^{12} suns. Observations of rapid variability imply that some QSOs and Seyferts emit their power from a region not more than a few light days across. To explain these basic properties, great power and small size, is the first task of any theory.

One of the most appealing suggestions is the idea that QSOs may involve accretion onto a massive black hole in a galactic nucleus (Lynden-Bell 1969). Black holes can extract energy from infalling matter with high efficiency, and they easily meet the requirement of small size. The probable discovery of a black hole in Cygnus X-1 lends credence to the existence of black holes in other astrophysical environments, including galactic nuclei.

In this essay, we propose a picture in which a given galaxy undergoes intermittent flashes of Seyfert/QSO activity. These flashes are fueled by gas that gradually accumulates in the nucleus and then suddenly collapses onto a central, massive black hole. The basic tenet of the model is that plausible sources of gas are insufficient to power a QSO continuously but that they can fuel intermittent flashes of high luminosity. We find that the flash picture provides a new understanding of some observed features of QSOs and Seyfert galaxies.

First, we consider various processes for supplying gas in a galactic nucleus. For a black hole of mass $M_H = 10^8\ M_\odot$, the Eddington limit is $L_{Edd} \approx 10^{12.5}\ L_\odot$, a modest QSO luminosity. If accretion produces a luminosity $L = \epsilon \dot{M} c^2$ with $\epsilon \simeq 0.1$, then an accretion rate $\dot{M}_{Edd} \approx 1\ M_{\odot}\ yr^{-1}$ will give $L \approx L_{Edd}$. As a representative example we consider a black hole with $M_H = 10^8\ M_{\odot}$ in a nucleus characterized by an isothermal core of mass $3 \times 10^8\ M_{\odot}$ and density $10^7\ M_{\odot}\ pc^{-3}$. The core radius is then 1.9 pc, and the rms stellar velocity is ~600 km s^{-1} in accordance with the virial theorem. Other plausible parameters for the nucleus give the same qualitative conclusions.

Possible sources of gas to feed the hole include tidal disruption (Hills 1975), stellar collisions, and stellar evolution. Young, Shields, and Wheeler (1977) found that orbit diffusion limits the rate of tidal disruption to a value $\dot{M}_{tide} << \dot{M}_{Edd}$. The stars in the nucleus wander into disruptive orbits in a time $\sim 5 t_R$ where the relaxation time, t_R, for the adopted parameters is $\sim 8 \times 10^{10}$ yrs. Therefore $\dot{M}_{tide} \approx 8 \times 10^{-4}\ M_{\odot}\ yr^{-1}$. Stellar collisions produce gas by ejection during collisions and by coalescence leading to massive stars that evolve quickly and shed much of their mass. Studies by Spitzer and Saslaw (1966) and Sanders (1970) conclude that the average collision ejects ~5 percent of the mass of one star; thus, $\dot{M}_{ej} \approx 0.05\ M_c/t_{coll} \approx 8 \times 10^{-4}\ M_{\odot}\ yr^{-1}$, where for our parameters the collision time is $t_{coll} \approx 1.9 \times 10^{10}$ yr (Spitzer and Saslaw 1966). We estimate that coalescence leads to liberation of much of the stellar mass on a timescale $\sim 2.5\ t_{coll}$, so that $\dot{M}_{coal} \approx 6 \times 10^{-3}\ M_{\odot}\ yr^{-1}$. Finally, ordinary stellar evolution produces gas in the form of planetary nebulae, stellar winds, and supernovae. Taking $\dot{M}_{ev} \approx M_c/2 \times 10^{10}\ yr \approx 10^{-2}\ M_{\odot}\ yr^{-1}$, we see that this rate slightly exceeds tidal disruption and stellar coalescence but still fails to approach $\dot{M}_{Edd}$.

Evidently, these processes are inadequate to fuel a 10^8 $M_\odot$ hole hear its Eddington limit in a steady fashion. We are therefore led to ask, can gas accumulate in the nucleus over some period τ_{acc}, and then quickly collapse to the center and feed the hole at $\dot{M}_{Edd}$ for a brief but spectacular episode? One possible mechanism for doing this is suggested by the work of Spitzer and Saslaw (1966). Gas evolved in the nucleus will be shocked to a temperature $\sim 1.3 \times 10^7$ K determined by the virial velocity. As the total mass, M_{acc}, of the accumulating gas increases, the density rises, and the bremsstrahlung cooling rate ($\tau_b \approx 3.5 \times 10^7 \, n^{-1}$ yr) drops below the gas accumulation time $\tau_{acc} \equiv M_{acc}/\dot{M}$. This robs the gas of its supporting pressure and causes a runaway collapse. This collapse may proceed coherently, with most of the gas arriving at the center during an interval shorter than the free-fall time (Mathews 1972). We suggest that the gas then is eaten by the black hole at roughly the Eddington limit until the supply is exhausted.

If gas is evolved in the nucleus that we have adopted at $\sim 10^{-2}$ $M_\odot$ yr^{-1}, then collapse occurs when a mass $M_{acc} \approx 5 \times 10^2$ $M_\odot$ accumulates over a period $\tau_{acc} \approx 5 \times 10^4$ yr. This charge of gas can maintain a power $\sim L_{Edd}$ for a "flash time" $\tau_f \approx 5 \times 10^2$ yr. This value of τ_f may seem short but there is no stringent limit on the duration of a single flash other than the fact that NGC 1068 had a Seyfert nucleus 70 years ago (Fath 1908). Even so, more careful examination may show that the mechanism by which the gas enters the hole, such as an accretion disk, may impose its own instability timescale and save up a number of charges of gas for a more prolonged luminous episode.

We now consider the evolution of the hole with the assumption that ordinary stellar evolution provides most of the accretion. If the number of stars with mass between m and m + dm is (dN/dm)dm and m_u is the largest mass still on the main sequence, then $\dot{M}_{ev} \approx m_u (dN/dm)_{m_u} (dm_u/dt)$. For main sequence lifetimes $\tau_{MS} \propto m^{-2}$, we have $dm_u/dt \propto m^{-1.5}$. If we take a Salpeter (1955) mass function $dN/dm \propto m^{-2.35}$, then $\dot{M}_{ev} \propto t^{-0.83}$. The collapse condition then gives $\tau_{acc} \propto t^{0.41}$ and $M_{acc} \propto t^{-0.41}$. Successive episodes of accretion add to the mass of the black hole. If this accounts for most of the hole's mass, then $M_H(t) = \int \dot{M}_{ev} dt \propto t^{0.18}$. The luminosity during a flash is $L_{Edd} \propto t^{0.18}$, and the duration is $\tau_f \propto t^{-0.59}$. As time goes on, the flashes become briefer, less frequent, and slightly more luminous.

This evolution is illustrated in Figure 1, where we have assumed (arbitrarily) $M_H = 10^4 M_\odot$ at $t = 10^{8.5}$ years. The hole shines continuously at the Eddington limit and grows exponentially until $\dot{M}_{Edd}$ drops below $\dot{M}_{ev}$. The flash phase then begins. (In Figure 1, τ_{acc} has been exaggerated a factor 2 x 10^4, and τ_f, a factor 10^5.)

The flash model accounts for several observed properties of QSOs and Seyferts. The duty cycle of the flashes decreases with time as $\tau_f/\tau_{acc} \propto t^{-1}$, in qualitative agreement with the observation that there were more QSOs in the past at a given moment than there are today (Schmidt 1976). The value $\tau_f/\tau_{acc} \propto 10^{-2}$ estimated above agrees with the observation that roughly one percent of spiral galaxies contain Seyfert nuclei and hence we predict that most spiral galaxies go through Seyfert phases.

Seyfert galaxies, in this picture, occur in less massive nuclei than do QSOs; the black hole has grown to only $M_H \approx 10^6$ to 10^8 $M_\odot$ because of a relatively small value of $\dot{M}_{ev} \propto M_c$. The flash model may also account for the observation that some radio galaxies have extended radio sources with no current activity in the nucleus. A merit of the flash model is that it avoids the problem that radiation pressure on grains could limit accretion by the black hole to a value $<<\dot{M}_{Edd}$ (Lynden-Bell and Rees 1971). This is because a given charge of gas falls to the vicinity of the hole during the low luminosity phase.

We note that many of these successful features of the model do not depend on the particular mechanism for regulating the interval between flashes. The flash luminosity at a given time is fixed by $\int \dot{M}_{ev}\, dt$, and the duty cycle is fixed by $\dot{M}_{Edd}/\dot{M}_{ev}$.

Support for the idea of intermittent activity in galactic nuclei, on timescales of 10^6 years or less, is provided by the observation of discrete features in the velocity fields near the nuclei of NGC 1068 (Walker 1968) and the Milky Way (Sanders, Wrixon and Penzias 1972). Another argument for intermittent Seyfert activity in NGC 1068 can be made on the basis of Walker's (1968) velocity measurements. From these, we estimate an upper limit of 2×10^8 $M_\odot$ for a central point mass. The current luminosity of NGC 1068 is 7×10^{44} ergs s^{-1} (Jameson et al. 1974) requiring accretion onto a black hole at a rate of 0.12 $M_\odot$ yr^{-1} if $\varepsilon = 0.1$. If this had continued for 10^{10} years, the hole would have grown to 1.2×10^9 $M_\odot$, which is inconsistent with the above limit. This implies that NGC 1068 has shone at its present luminosity for less than one-sixtieth of the Hubble time, consistent with the duty cycle $\sim 10^{-2}$ estimated for our model.

The basic elements of our model are a massive black hole in a galactic nucleus, and the build up and collapse of gas in the nucleus. These ideas have been discussed separately before. The novelty of the present work is to combine these features into a coherent picture in which gas collapsing on the hole leads to repeated episodes of luminous accretion and growth of the hole. The fundamental strength of the model is that it begins with reasonable conditions for a galactic nucleus and naturally develops the extreme conditions of a QSO.

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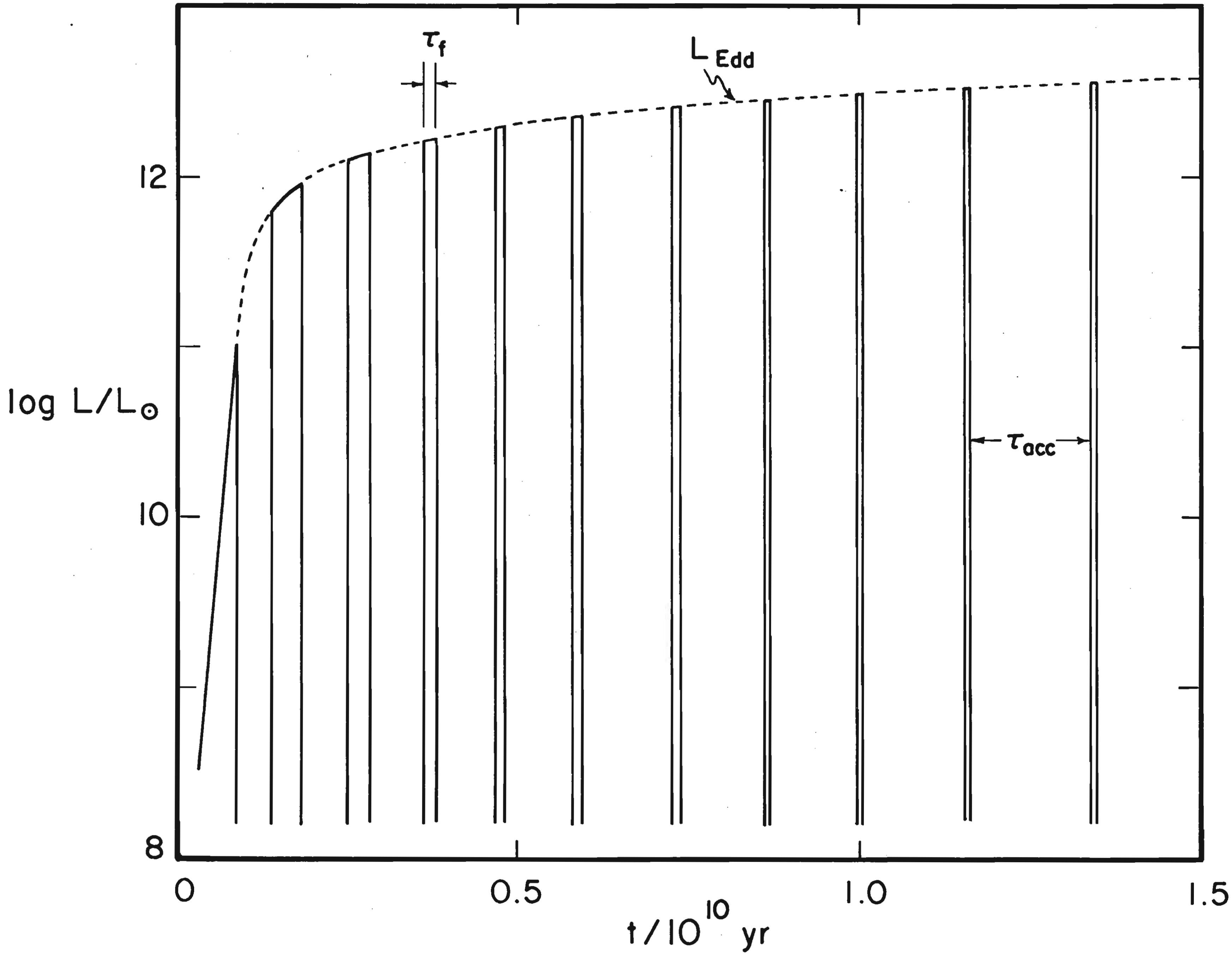
Figure Captions

Figure 1 - The luminosity of the flash model of QSOs is shown as a function of time. The accumulation timescale τ_{acc} has been scaled by a factor of 2×10^4 and the duration of the flash τ_f by a factor of 10^5 for purposes of illustration.



τ_f
L_{Edd}
τ_{acc}
log L/L⊙
12
10
8
0
0.5
1.0
1.5
$t/10^{10}$ yr

Biographical Sketch

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