Are Ultra-Luminous X-ray Sources Intermediate Mass Black Holes Accreting from Molecular Clouds?

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ABSTRACT

The origin and nature of Ultra-Luminous X-ray sources (ULXs) is a contentious and controversial topic. There are ongoing debates about the masses of the objects responsible, their sources of mass for accretion, and their relation to stellar populations in galaxies. A new picture of these objects is proposed in which they are intermediate-mass black holes confined to the disks of their host galaxies and accreting from the interstellar medium. They are then preferentially found in or near molecular clouds. This model correctly predicts the shape of the observed luminosity function and requires only a very small fraction of the baryonic mass of a galaxy to be in the form of intermediate-mass black holes. Because the X-rays they produce strongly heat nearby interstellar gas and because they move relatively rapidly in and out of dense regions, ULXs are predicted to have brief episodes of high luminosity, perhaps $\sim 10^5$ yr in duration, but they may recur many times.

1. Introduction

Ultra-Luminous X-ray Sources (ULXs) are a class of X-ray source with apparent luminosities in the range $10^{39} - 10^{41}$ erg s$^{-1}$ seen in many nearby galaxies (see, e.g., the reviews
by van der Marel 2003 and Miller & Colbert 2004). Because these luminosities, if emitted isotropically, would be super-Eddington coming from ordinary stellar black holes with masses \( \sim 10M_\odot \), their nature is the subject of much controversy. Some believe that they are black holes of mass \( \sim 10^2\mathrm{--}10^3M_\odot \) (Colbert & Mushotzky 1999, Miller & Hamilton 2002, Cropper et al. 2004). Others argue that they are stellar mass black holes whose radiation only appears to be super-Eddington because it is strongly anisotropic, due either to disk transfer effects (King et al. 2001), or relativistic beaming (Körding et al. 2002). Still others suggest that they are stellar mass black holes able to radiate at super-Eddington rates by means of a magnetic confinement mechanism (Begelman 2002) or non-conservative highly super-Eddington accretion (King 2004).

One clue to their origin is that they are often found close to regions of active star formation (Matsushita et al. 2000, Roberts et al. 2002, Zezas et al. 2002, Kilgard et al. 2002, Roberts et al. 2004). In fact, there are sometimes indications (either through associated molecular line emission: Matsushita et al. 2000, or large column density X-ray absorption: Zezas et al. 2002) that these X-ray sources are within dense molecular clouds. Initial claims (e.g., Angelini et al. 2001) that there were numerous ultra-luminous X-ray sources in early-type galaxies have been reduced by Irwin et al. (2003) on the ground that all but two of the brighter sources are chance superpositions (but see Jeltema et al. 2003 for a better-supported example). In this paper we therefore explore the possibility that ULXs (or at least the more numerous variety in star-forming regions) may be intermediate mass black holes that, when placed in dense molecular clouds, accrete mass at a high enough rate to become X-ray luminous.

2. The Velocity Dispersion

2.1. Centrality of the Black Hole Velocity Dispersion

The luminosity of a black hole accreting from the interstellar medium depends on its mass, the ambient gas density, and its speed relative to the surrounding gas:

\[
L \sim 4 \times 10^{31}(\eta/0.1)M^2n\left(\frac{\Delta v}{10\text{ km s}^{-1}}\right)^{-3}\text{ erg s}^{-1},
\]

where \( \eta \) is the radiative efficiency in rest-mass units, \( M \) is the mass of the black hole in solar masses, and \( n \) is the density of atoms in \( \text{cm}^{-3} \). To make this estimate, we have used the classical Bondi theory in the limit that the relative speed between the black hole and the surrounding gas is larger than the thermal speed of the gas. Although stellar-mass black holes accreting from regions of diffuse gas will never come close to radiating the
luminosities observed from ULXs (King et al. 2001, Agol & Kamionkowski 2002), black holes with $M \gtrsim 300$ accreting from dense molecular clouds can easily achieve luminosities $\gtrsim 10^{39}$ erg s$^{-1}$.

That is, this luminosity level can be achieved under two provisos: that $\Delta v$ is not $\gg 10$ km s$^{-1}$, and the inner part of the accretion flow is disk-like so that relativistic radiative efficiency can be achieved (see §3). As equation 1 makes clear, the accretion luminosity is then extremely sensitive to $\Delta v$.

In fact, the velocity dispersion of the black holes also enters in a second important way, governing the fraction of the population of black holes found within a molecular cloud at any given moment. Agol & Kamionkowski (2002) estimated that the volume filling fraction of dense molecular clouds near the Sun is $\sim 10^{-3}$ (for this purpose, “dense” is defined as density greater than $n_{\text{min}} = 100$ cm$^{-3}$). If we use their equation 8 scaled to the data from galaxies with numerous ULXs such as M82 (Walter et al. 2002) or the Cartwheel galaxy NGC 4038/9 (Wilson et al. 2003), the volume filling fraction $f_{\text{mol}}$ in the galactic midplane in these galaxies could be $\sim 50$ times larger (where there are probably factors of several uncertainty owing to uncertainty in the CO/H$_2$ conversion ratio). The scale height of molecular clouds in the Galaxy is $\simeq 75$ pc, corresponding to a velocity dispersion $\sigma_{\text{mol},z} \simeq 10$ km s$^{-1}$; if the black holes have a vertical velocity dispersion $\sigma_{\text{bh},z} > \sigma_{\text{mol}}$, the probability that any particular black hole is found within a molecular cloud becomes $f_{\text{mol}} \sigma_{\text{mol},z} / \sigma_{\text{bh},z}$.

Moreover, because the accretion rate is so sensitive to relative speed, the fraction of black holes resident in a molecular cloud, yet capable of accreting at a significant rate, is further reduced by the fraction of phase space in which the velocity of the black hole is matched closely to the orbital velocity of the molecular cloud. When $\sigma_{\text{bh}} \gg 10$ km s$^{-1}$, this fraction is $\sim (\sigma_{\text{bh}}/10$ km s$^{-1})^{-3}$.

Thus, for all these reasons, the critical factor in determining the efficiency of intermediate mass black holes accreting from the interstellar medium is their distribution of velocities relative to the orbital velocity of molecular clouds.

### 2.2. Initial Conditions for the Black Hole Velocity Dispersion

As with many problems, there are issues of both “nature” and “nurture”. We start with the initial state of the black hole orbits, but these orbits are likely to evolve over a Hubble time.
2.2.1. Black holes formed in mini-haloes

In one popular scenario for the origin of intermediate mass black holes, they are formed at high redshift in dark matter “mini-haloes” (Madau & Rees 2001, Schneider et al. 2002) when heavy element abundances are essentially nil, so that the stellar initial mass function strongly favors stars with $M > 10^3$ (Bromm et al. 1999, Abel et al. 2000). It is possible that as much as $\sim 10^{-4}$ of the baryonic mass could end up in intermediate mass black holes, arriving there through this pathway (Madau & Rees 2001). These mini-haloes then deliver the black holes to larger galaxies in mergers.

Because the black holes are as collisionless as the dark matter, one would expect their orbits in post-merger galaxies to be similar to the dark matter’s, i.e., appropriate to a galactic halo population (Schneider et al. 2002). Some black holes may carry with them remnants of their dark-matter haloes, and the added mass would enhance dynamical friction, but those that settle deep into the post-merger galaxy are likely to lose these haloes by tidal stripping (Islam et al. 2003). The typical relative speed between an intermediate mass black hole of this sort and molecular clouds in the galactic disk would then be $\sim 200$ km s$^{-1}$, far too large to permit accretion rates from the interstellar medium capable of sustaining an ultra-luminous X-ray source. Only that small fraction whose velocity fortuitously coincides with a molecular cloud’s would be able to accrete at a substantial rate. Moreover, when considerations of accretion and black hole binary dynamics are added to black hole merger rates, the number of extra-nuclear black holes per galaxy acquired by this mechanism is likely to be relatively small (Volonteri et al. 2003).

Except for those black holes whose orbits take them either very close to the center of the galaxy (within $\sim 10$ pc: Madau & Rees 2001) or nearly parallel to the disk plane (so that the time-averaged mean density of matter encountered is $\gtrsim 1M_\odot$ pc$^{-3}$), dynamical friction will do little to black holes on such orbits even over a Hubble time. Thus, for the most part, the “nurture” side has little effect on the character of black hole orbits if they are formed in this way.

2.2.2. Black holes formed late from primordial abundance gas

Formation in mini-haloes is not, however, the only conceivable pathway to creation of intermediate mass black holes. It is possible, for example, that gas of primordial elemental abundance (i.e., $< 3\times 10^{-4}$Z$_\odot$ in the estimate of Bromm et al. 2001) also finds its way directly into the disks of galaxies. If stars are then created from this gas, one would still expect their initial mass function to favor high-mass stars. A population of intermediate-mass black holes
with disk orbits would soon result. As will be shown in §3, if the intermediate-mass black holes are a disk population, only a very small total mass is required in order to produce the observed ULXs. The question, then, is whether some small fraction of the Universe’s baryons can be kept at primordial abundance until relatively late (perhaps $z \lesssim 1$), be captured at that point into mature disk galaxies, and undergo star formation before significant chemical mixing occurs.

Most of the gas in the Universe is first “polluted” when it is pulled into a mini-halo and exposed to star formation there. However, we do not know whether this is true of all the baryons. Although the standard CDM power spectrum of density fluctuations is “blue” enough that most matter should be accreted into small-mass structures early on, it seems implausible that this should happen to absolutely all baryons. Unfortunately, quantitative estimates of the completeness of this process are very difficult, either because exceptions to baryon capture are ruled out by construction (as in the Press-Schechter formalism) or because of limitations in resolution (in the case of numerical simulations). At the very least, there should be a high-wavenumber cut-off beyond which mini-haloes cannot accrete gas because, for example, their potential depths are less than the temperature of the smoothly-distributed baryons. We suggest, therefore, that a small fraction of the baryons escape capture into mini-haloes at high redshift.

It is also possible that some gas that is accreted onto small structures at high-redshift is nonetheless preserved from contamination with heavy elements. Shock waves driven by the first stars in these structures could eject gas from low-binding-energy mini-haloes without substantial mixing; tidal encounters could remove gas from their exteriors, etc.

Although parts of the intergalactic medium do contain heavy elements (as seen, for example, in quasar absorption line systems), the absence of stellar stirring may keep the IGM sufficiently quiescent as to limit mixing processes (see, e.g., the discussion of the many uncertainties in Madau et al. 2001). The median of the [C,O/H] distribution in Ly$\alpha$ absorption systems is $\sim 10^{-3}$ Solar, but there is a wide range of abundances seen (Simcoe et al. 2004). Indeed, Simcoe et al. argue that only about half the intergalactic baryons have been enriched to greater than $10^{-3.5}$ Solar abundance in C and O by $z \approx 2.5$.

On the basis of these (admittedly loose) arguments, we conclude that it is at least a reasonable possibility to suppose that some primordial abundance material can be injected into galactic disks at relatively late times. The black holes created from this gas, unlike the ones created in mini-haloes, would be born with orbits in the galactic disk. Their initial velocity dispersion relative to the local circular orbital velocity should therefore be as small as for other young stars ($< 10\text{ km s}^{-1}$: Wielen 1977). The absence of primordial abundance stars in the Galactic disk provides only a weak constraint on this mechanism if the initial
mass function was, in fact, strongly weighted toward high-mass stars because in that case only very few low-mass long-lived stars would have formed from this gas.

2.2.3. Black holes formed from stellar mergers

Another way intermediate mass black holes could be created inside a galactic disk is through runaway merger of massive stars in a young cluster (Portegies Zwaart et al. 2004). This mechanism does not depend on having low heavy-element abundances in the star-forming gas, so it can occur at any time in the life of the galaxy. Once created, these black holes, too, should have random velocities characteristic of young stars or even smaller.

2.3. Time-evolution of the Black Hole Velocity Dispersion

The mechanisms that control the evolution of stellar random motions are not entirely understood, but there are two strong candidates: encounters with molecular clouds (Spitzer & Schwarzschild 1951, 1953) and irregularities in the galactic potential (Barbanis & Woltjer 1967, Carlberg & Sellwood 1985; Binney & Lacey 1988, Jenkins & Binney 1990). Both should act just as effectively on intermediate mass black holes as on stars because, even if their masses are $\sim 10^3 M_\odot$, these black holes are still much less massive than either giant molecular clouds or the mass contributing to galactic potential fluctuations.

On that basis, the observed velocity dispersion of old normal stars provides an approximate upper bound on the dispersion of intermediate mass black holes. For example, in our Galaxy, the vertical dispersion of the oldest stellar population is $\simeq 36 \text{km s}^{-1}$, while its radial dispersion is $\simeq 62 \text{km s}^{-1}$ (Reid et al. 2002). However, the dispersions of intermediate mass black holes may be significantly smaller for two reasons: if they were created relatively recently (by the merger-in-clusters mechanism, for example), or if dynamical friction against comparatively slowly-moving young ordinary stars diminishes their speed relative to the local standard-of-rest.

To estimate the magnitude of these mechanisms, we follow Jenkins & Binney (1990) and Binney & Lacey (1988): We describe the evolution of the black hole distribution function in terms of a Fokker-Planck equation and use their formalism for estimating the magnitudes of the coefficients in that equation. The basic equation is then

$$\frac{\partial f}{\partial t} = -\nabla_E (\bar{g} f) + \frac{1}{2} \nabla_E (\bar{\mathbf{D}} \cdot \nabla_E f),$$  

where the distribution function is with respect to random kinetic energy in the vertical and
radial directions, $\nabla_E$ is the gradient with respect to kinetic energy associated with each axis, $\vec{g} = \langle \dot{E}_R \rangle \hat{R} + \langle \dot{E}_z \rangle \hat{z}$, and $\mathbf{D}$ is the $2 \times 2$ matrix of diffusion coefficients.

Dynamical friction accounts for $\vec{g}$:

$$g_i = -4\pi \ln \Lambda G^2 M_\odot \rho \mathcal{M} \chi / v_i. \quad (3)$$

Here $\rho$ is the smoothed density of stars, $v_i = \sqrt{2E_i}$ is the black hole’s random speed in the $i$th direction, and

$$\chi \equiv \text{erf}(X) - 2X \exp(-X^2)$$

for $X = |v_i|/(\sqrt{2}\sigma_*)$, where $\sigma_*$ is the stellar velocity dispersion. Evaluating $\vec{g}$ for typical values gives

$$g_i = -2.3 \times 10^{-6} (\mathcal{M}/1000) \left( \frac{v_i}{10 \text{ km s}^{-1}} \right)^{-1} \left( \frac{\rho}{0.1 M_\odot \text{pc}^{-3}} \right) \chi \text{ cm}^2 \text{ s}^{-3}. \quad (4)$$

We choose a stellar density of $0.1 M_\odot \text{pc}^{-3}$ as our fiducial value because it is the local density near the Sun (Merrifield & Binney 1999).

In the Jenkins & Binney (1990) formulation, all four of the components in the diffusion coefficient matrix have contributions from scattering with molecular clouds, but potential fluctuations contribute only to the $R-R$ component. According to their estimate, the characteristic scale for all contributions is set by

$$C \equiv \frac{8}{\pi} \ln \Lambda G^2 \mu_c M_c \nu_z = 6 \times 10^6 \left( \frac{\mu_c}{2 M_\odot \text{pc}^{-2}} \right) \text{ cm}^4 \text{ s}^{-5}, \quad (5)$$

where $\mu_c$ is the mean surface density of molecular clouds, $M_c$ is the mass-weighted mean cloud mass, and $\nu_z$ is the frequency of harmonic motion in the vertical direction. In the case of fluctuations in the potential, $D_{RR} \simeq \beta J_1^2(\mathcal{K}a) C$, where $\beta \simeq 90$ is a coefficient determined by fitting to data, $J_1$ is the first-order Bessel function, $\mathcal{K}$ essentially defines the wavenumber of the disturbance, and $a = \sqrt{2}v_R/\kappa$ is the amplitude of epicyclic motion for radial epicyclic frequency $\kappa$.

The relative importance of diffusion in velocity space and dynamical friction can be gauged by comparing the characteristic rates with which they alter the distribution function, $t_{\text{fric},i}^{-1} \sim |g_i|/v_i^2$ and $t_{\text{diff},i}^{-1} \sim D_{ii}/v_i^4$:

$$t_{\text{diff},i} / t_{\text{fric},i} \sim 1 \left( \frac{\rho}{0.1 M_\odot \text{pc}^{-3}} \right) \left( \frac{\mathcal{M}}{1000} \right) \chi \left( \frac{\mu_c}{2 M_\odot \text{pc}^{-2}} \right)^{-1} \left\{ \begin{array}{ll} v_{10}^{-1} & i = R \\ 0.25v_{10} & i = z \end{array} \right. \quad (6)$$

The dependence on $v_{10}$ reflects the assumption that scattering by potential fluctuations dominates $D_{RR}$. When the scaling quantities have their fiducial values, the two rates are
comparable. Because diffusion by potential fluctuations increases in strength as the random speed grows, whereas scattering by clouds is independent of the random speed, dynamical friction may be better able to restrain the growth of vertical motions than horizontal motions.

Unfortunately, because there remain quantitative problems using any of these prescriptions to predict the actual stellar dispersions in the Solar neighborhood (G. Gilmore, private communication), these scalings should not be taken as definitive. We are thus left with the conclusion that the random speeds of intermediate mass black holes injected early into a galactic disk are unlikely to be greater than those of old stars ($\approx 40\text{–}60\text{ km s}^{-1}$), and it is possible, particularly for those with masses $\gtrsim 1000\,M_\odot$, found in regions of relatively high stellar density, that their random speeds may be rather closer to those of young stars ($\approx 10\text{ km s}^{-1}$).

3. Population Estimates

As remarked above, the luminosity function of black holes in a galaxy accreting from its interstellar medium depends on their mass distribution, their velocity distribution, and the distribution of gas density. To predict the luminosity function, we employ a formalism very similar to that of Agol & Kamionkowski (2002), i.e.,

$$\frac{dN}{dL} = \int dM \int d^3 v \int d^3 x \int dn_{BH} f(v) \frac{dn_{BH}}{dM} p(n_g, \vec{x}) \delta \left[ L - 4\pi n_g \bar{m} c^2 \eta (GM)^2 / v^3 \right],$$

where $\vec{x}$ is position in the galaxy, $n_g$ is the gas density, $n_{BH}$ is the density of intermediate mass black holes, $f(v)$ is the velocity distribution function of the black holes normalized to unity, $dn_{BH}/dM$ is the mass function of the black holes similarly normalized to unity, and $p(n_g, \vec{x})$ is the probability of finding gas of density $n_g$ at location $\vec{x}$. For this toy-model, we suppose that the vertical distribution of both the black hole density and the gas density are Gaussians, but with scale-heights determined by their differing velocity dispersions. In the interest of simplicity, we likewise suppose that the black hole velocity distribution is an isotropic Gaussian. Following Agol & Kamionkowski, we suppose that $p(n_g, \vec{x}) \propto n_g^{-\beta}$ from $n_{min}$ to $n_{max}$; they take $\beta \approx 2.8$, $n_{min} = 100$ cm$^{-3}$ and $n_{max} = 10^5$ cm$^{-3}$. Lastly, for no particularly good reason other than ease of computation, we write $dn_{BH}/dM \propto M^{-\alpha}$ from $M_{min}$ to $M_{max}$, where we imagine that $1 < \alpha < 3$, $M_{min} \sim 100M_\odot$, and $M_{max} \sim 10^4M_\odot$.

With those assumptions,

$$\frac{dN}{dL} = \frac{2^{5-2\beta}(2\pi)^{9/2-2\beta}}{3} \frac{(\alpha - 1)(\beta - 1)}{(\beta - 2)(3 - \alpha)} f_{mol} \frac{h_g}{\hbar} \left( M_{min} / M_{max} \right)^{\alpha - 1} \frac{L_* \, N_{tot}}{L} \exp \left[ -(1/2)(L_*/L)^{2/3} \right],$$

(8)
where \( h, h_g \) are the scale-heights of the black holes and the gas, respectively, and we suppose \( h_g < h \); \( L_* = 4\pi n_{\text{min}} mc^2\eta (GM_{\text{max}})^2/\sigma_{\text{bh}}^3 \) is a characteristic luminosity, the luminosity of a maximum-mass black hole accreting from a minimum density cloud; and \( N_{\text{tot}} \) is the total number of intermediate mass black holes in the galaxy. Strikingly, the predicted shape of \( dN/dL \), i.e., \( \propto L^{-2} \), is independent of \( \beta \) and \( \alpha \). This result follows from the coincidence that the Bondi accretion rate is \( \propto v^{-3} \) while we have guessed that the black hole velocity distribution function is quasi-thermal, i.e., \( dn \propto \exp(-v^2/2\sigma^2)d(v^3) \).

Rewriting equation 1 in terms of the characteristic quantities, we see that

\[
L_* = 6 \times 10^{39} \left( \frac{\eta}{0.1} \right) \left( \frac{M_{\text{max}}}{10^4} \right)^2 \left( \frac{n_{\text{min}}}{100\text{cm}^{-3}} \right) \left( \frac{\sigma_{\text{bh}}}{40\text{km s}^{-1}} \right)^{-3} \text{erg s}^{-1}. \tag{9}
\]

Making use of this lower cut-off to the luminosity function, we find that the fraction of all intermediate mass black holes found in regions where the Bondi accretion rate is great enough to support ULX-level luminosity (defined here as \( L > L_* \)) is \( \sim f_{mol}(h_g/h)(M_{\text{min}}/M_{\text{max}})^{\alpha-1} \). A change in the (somewhat arbitrary) definition of \( n_{\text{min}} \) would be reflected in a change in the radiating fraction through its implications for \( f_{mol} \).

As already discussed, \( f_{mol} \) could rise to as great as \( \sim 0.05 \) where star formation is occurring at a rapid rate. If \( h_g/h \approx 1/4 \), as implied by our guesses about the velocity dispersions, the total number of intermediate mass black holes in a galaxy displaying \( \sim 10 \) ULXs would be \( N_{\text{BH}} \sim 800(M_{\text{max}}/M_{\text{min}})^{\alpha-1} \). This scaling assumes \( 1 < \alpha < 3 \); the dependence on \( M_{\text{max}}/M_{\text{min}} \) arises because the lowest-mass black holes are likely to dominate in number, but because the accretion rate is \( \propto M^2 \), the highest-mass contribute disproportionately to the numbers of bright objects. The total mass in intermediate-mass black holes in a galaxy is \( \sim f_{mol}^{-1}(h_g/h)M_{\text{max}}N(L > L_*)F \), where \( F = 1 \) if \( \alpha < 2 \) or \( (M_{\text{max}}/M_{\text{min}})^{\alpha-1} \) if \( \alpha > 2 \). For example, if \( \alpha = 2 \) and \( M_{\text{max}}/M_{\text{min}} = 100 \), the total mass in intermediate-mass black holes is \( \sim 4 \times 10^6 N(L > L_*)M_\odot \). This would be a small fraction, indeed, of the total baryonic mass of the galaxy.

It is encouraging that the slope of the luminosity function predicted in equation 8 (-1 for the cumulative function) is in quite good agreement with the slope of the luminosity function above \( 10^{39} \) erg s\(^{-1}\) found by Kilgard et al. (2002) in the Antennae galaxies.

On the other hand, in order to produce the observed population of ultra-luminous X-ray sources by means of that small fraction of intermediate mass black holes formed in mini-haloes and capable of radiating brightly, the total number of such black holes in a typical galaxy must be very large. In that case, the bright fraction is only \( \sim f_{mol}(\sigma_{\text{mol}}/\sigma_{\text{bh}})^4 \sim 10^{-6} \), and to produce 10 ULXs in a galaxy would likely require more than \( 2 \times 10^9 M_\odot \) in intermediate mass black holes. Thus, if ULXs are indeed intermediate-mass black holes accreting from
dense gas in the host galaxy’s interstellar medium, possessing disk-like kinematics is essential: the total mass required by a bulge- or halo-like population would be implausibly large. The only escape from this argument comes from the possibility that black holes of this variety might accrete, not from the general interstellar medium, but from baryonic matter they brought with them from the mini-halo in which they were created. If this gas is substantially more tightly bound to them than the dark matter, it would be better able to resist tidal stripping, but fairly extreme assumptions about this process are required to create large numbers of ultra-luminous X-ray sources (Islam et al. 2003).

4. Impact on the Molecular Cloud and the Duty Cycle of Activity

Such a large ionizing luminosity inflicted upon a nearby molecular cloud would be sure to change its state dramatically. For example, Neufeld et al. (1994) described the impact of X-rays impinging on nearby molecular gas in terms of the parameter $F/(N^{0.9}p)$, where $F$ is the X-ray flux, $N$ the gas’s column density, and $p$ its pressure. They found that when this parameter exceeds $10^{-13}$ cgs, molecules are destroyed. In terms of fiducial ULX numbers, the Neufeld et al. parameter in the circumstances of interest here is $\sim 10^{-10}L_{40}(r/10 \text{ pc})^{-3}(n/100 \text{ cm}^{-3})^{-2}$ cgs, a thousand times greater than the critical value.

The surrounding gas should therefore be strongly photoionized and heated. In photoionization equilibrium, its state can be conveniently described in terms of the pressure-ratio photoionization parameter $\Xi \equiv L_{\text{ion}}/(4\pi r^2 n_{\text{H}} kT)$. When the density refers entirely to spherically-accreting gas, the ionization parameter can be rewritten as

$$\Xi = 3.9c \max(v_r, c_s)/c_s^2,$$

where $v_r$ is the radial infall speed, $c_s$ is the gas’s sound speed, and a fully-ionized H-dominated chemical composition has been assumed. Values of $\Xi > 1$ are to be expected out to distances where $v_r/c_s \sim c_s/c$, and where $\Xi \gg 1$, the gas will be hot and highly ionized.

Photoionization equilibrium is, in fact, a likely condition. Comparing the ionization timescale for H with the accretion timescale $t_{\text{acc}} \equiv r_A/v$ yields the ratio

$$\frac{t_{\text{ion},H}}{t_{\text{acc}}} = \tau_H^{-1} \left( \frac{L_{\text{ion}}/L}{\eta} \right) \left( \frac{\langle \epsilon \rangle}{\overline{m}c^2} \right),$$

where $\tau_H$ is the spectrally-averaged H-photoionization optical depth across radius $r$ if all the gas were neutral, and $\langle \epsilon \rangle$ is the mean ionizing photon energy. For our fiducial parameters, $\tau_H \simeq 6(M/1000)\sigma_{bh,40}n_{100}(\langle \epsilon \rangle/I_H)^{-3}$, so ionization balance should be easy to achieve in a flow-time provided the spectrum is not extremely hard.
If we assume a generic black hole spectrum, a sum of a thermal component with a typical ULX temperature of 0.2 keV (Miller et al. 2004) and a Comptonized power-law, the equilibrium (i.e., Compton) temperature for $\Xi \sim 30$ is $T_C \sim 10^7$ K. Heating by photoionization should be very rapid up to temperatures close to $T_C$; XSTAR (Kallman & Bautista 2001) calculations show that

$$t_{\text{heat}}/t_{\text{acc}} \sim 0.3(\frac{T}{T_C})^{2.5} n_{100}^{-1} r_{A,16}^{-1},$$  \hspace{1cm} (12)

where the accretion radius $r_A = 8.3 \times 10^{15} (\mathcal{M}/1000) \sigma_{bh,40}^{-2}$ cm. Only when a relatively small black hole is immersed in a relatively low density region might the temperature fail to reach equilibrium in an accretion time, but that is a combination of conditions yielding only a small luminosity (see eqn. 9). Black hole masses and interstellar densities high enough to provide a truly ULX luminosity imply rapid thermal equilibration.

When the temperature is raised close to $T_C$, the accretion flow is severely disrupted. Because the accretion rate is proportional to $c_s^{-3}$ when $c_s > v$, the accretion rate would fall relative to our nominal prediction by a factor $\sim 10^3$. An immediate drop in the luminosity by this factor would push $\Xi$ low enough to once again permit a lower-temperature equilibrium, but in fact there are likely to be significant time delays built into the system.

As Agol & Kamionkowski (2002) point out, density gradients within the molecular cloud are likely to imprint a small net angular momentum on the accreting matter. At a radius small compared to the accretion radius but large compared to the black hole, the flow must then flatten and form a disk. Their estimate applied in our context indicates that this typically happens at $r_{\text{disk}} \sim 2 \times 10^5 (\mathcal{M}/1000)^{2/3} \sigma_{bh,40}^{-10/3} r_g$. The accretion radius $r_A \sim 10^8 \sigma_{bh,40}^{-2} r_g$, so $r_g \ll r_A$, while at the same time $r_{\text{disk}} \gg r_g$, justifying our assumption of relativistic radiative efficiency.

The inflow time $t_{\text{in}}$ through a thin disk can be much longer than the disk orbital time $t_{\text{dyn}}$, as it is limited by the slow process of angular momentum transport. In terms of the $\alpha$-model of Shakura & Sunyaev (1973), $t_{\text{in}} \sim \alpha^{-1} (r/h)^2 t_{\text{dyn}}$, where $\alpha$ is the ratio of the mean vertically-integrated stress to the vertically-integrated pressure and $h$ is the thickness of the disk. Under the assumptions that gas pressure dominates the vertical support of the disk and that the disk is in inflow equilibrium at the Bondi accretion rate, we estimate that on the scale of $r_{\text{disk}}$,

$$h/r \sim 5 \times 10^{-3} \left(\frac{\alpha}{0.1}\right)^{-1/10} \left(\frac{\mathcal{M}}{10^4}\right)^{1/15} n_{100}^{1/5} \sigma_{bh,40}^{3/5}.$$

We then find that

$$\frac{t_{\text{in}}(r_{\text{disk}})}{t_{\text{acc}}} \sim 900 \left(\frac{\alpha}{0.1}\right)^{-4/5} \left(\frac{\mathcal{M}}{10^4}\right)^{13/15} n_{100}^{-2/5} \sigma_{bh,40}^{-16/5}.$$

\hspace{1cm} (14)
If ambient conditions remained constant for long periods of time, it might then be possible for the system to go through a limit-cycle with characteristic time

\[ t_{in}(r_{disk}) \sim 6 \times 10^5 \left( \frac{\alpha}{0.1} \right)^{-4/5} \left( \frac{M}{10^4} \right)^{28/15} n_{100}^{-2/5} \sigma_{bh,40}^{-31/5} \text{ yr.} \]  

While the ULX luminosity is low, accretion could proceed rapidly and the mass of the accretion disk surrounding the intermediate mass black hole could build; once the luminosity rises, further addition of material to the disk would be effectively halted. Note that as the disk surface density \( \Sigma \) grows, the accretion rate through the disk rises \( \propto \Sigma^{5/3} \), so that the luminosity at early stages lags somewhat behind the build-up of mass in the disk.

During the bright phase of the ULX, the energy it injects into the surrounding medium raises its temperature and pressure sharply. An expanding bubble should result, whose impact on the molecular cloud should be substantial. This should be true independent of the origin of the ULX, provided only that its radiative output is roughly isotropic. There is, however, a significant complication due to relative motion between the ULX and the molecular cloud: the change in relative position during the bright phase is \( \sim 25(\alpha/0.1)^{-4/5}(M/10^4)^{28/15} n_{100}^{-2/5} \sigma_{bh,40}^{-26/5} \) pc, a distance comparable to or larger than typical distinct dense regions in the interstellar medium. The lifetime in the bright phase might therefore be set by whichever is shorter, the residence time of matter in the accretion disk or the passage time for the black hole through a region of dense gas. Consideration of the time-dependent interplay between X-ray heating and motion of the black hole through a molecular cloud is an interesting topic best deferred to subsequent work.

5. Summary

We have shown that if intermediate-mass black holes are placed in the denser parts of the interstellar media of disk galaxies, Bondi accretion provides a great enough accretion rate to support the luminosities seen in Ultra-Luminous X-ray sources. The direct relation between ambient density and accretion rate automatically leads to a correlation between ULXs and regions of ongoing star-formation, as is observed. Indeed, to the extent that CO luminosity is a proxy for molecular gas content, it may be an indicator of ULX activity (E. Agol, private communication). Cross-comparison of CO maps with X-ray images for the nearer galaxies containing ULXs could then provide a test for this model. Note, however, that there is a rather strong selection bias for finding ULXs immediately outside dense molecular cloud regions: because their spectra are rather soft, they are very susceptible to soft X-ray absorption, and column densities commonly found in molecular clouds (\( \sim 10^{22} \text{ cm}^{-2} \)) block photons below \( \simeq 2 \text{ keV} \). As noted at the end of the last section, the residence time of
matter in their accretion disks can be long enough for black holes to move out into a clear region while still radiating brightly, having acquired their accretion fuel when in a denser neighborhood.

The central problem for this picture is whether sufficient intermediate-mass black holes can be created with orbits that keep them where the dense gas is located, i.e., close to the disk plane. Because it is believed that star-formation in primordial abundance gas is an especially efficient path to the production of intermediate-mass black holes (Bromm et al. 1999; Abel et al. 2000; Madau & Rees 2001; Schneider et al. 2002), the key question is whether enough gas free of heavy elements can be preserved until the orientation of present-day disk galaxies is set, brought into those disks, and then provoked into star-formation before it mixes with the interstellar medium of those galaxies. The likelihood of a positive answer to this question is raised by the fact that the amount required is a very small fraction of the total baryonic mass of contemporary disk galaxies, but any answer to it is at present highly speculative. Alternatively, intermediate-mass black holes might be formed as a disk population by runaway mergers in clusters (Portegies-Zwaart et al. 2004).

If intermediate-mass black holes are created within a galactic disk, they are likely to have random velocities no greater, and possibly rather smaller, than the old stars in the disk. Employing very simple assumptions, we predict that the shape of the luminosity function that results from such relatively small random speeds should agree with that observed: \( dN/dL \propto L^{-2} \). Particularly in galaxies with especially high molecular gas content, the total mass in intermediate-mass black holes necessary to create an active population with the numbers seen is quite modest, possibly as little as \( \sim 10^7 M_\odot \).

However, placing such a strong X-ray source in an interstellar cloud disrupts the very conditions that allow rapid accretion to take place. Time delays in the accretion disk that should form well within the nominal Bondi accretion radius allow accretion to continue long enough to build up a reservoir that can supply the X-ray source for \( \sim 10^5 \) yr after it ionizes and heats its environment so thoroughly that further Bondi accretion is shut off, or, depending on which happens first, it leaves the region of dense gas in which it accumulated the mass in its accompanying disk. It is likely that individual sources therefore undergo frequent cycling between bright and dim episodes. The effects on surrounding molecular gas deserve further detailed investigation.

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