Populations of High Energy Sources in Galaxies
Proceedings IAU Symposium No. 230, 2005
E. J. A. Meurs & G. Fabbiano, eds.

doi:10.1017/S1743921306008520

Ultra-Luminous X-ray Sources: Evidence for Very Efficient Formation of Population III Stars Contributing to the Cosmic Near-Infrared Background Excess?

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Abstract. Accumulating evidence indicates that some of ultra-luminous X-ray sources (ULXs) are intermediate mass black holes (IMBHs), but the formation process of IMBHs is unknown. One possibility is that they were formed as remnants of population III (Pop III) stars, but it has been thought that the probability of being an ULX is too low for IMBHs distributed in galactic haloes to account for the observed number of ULXs. Here we show that the number of ULXs can be explained by such halo IMBHs passing through a dense molecular cloud, if Pop III star formation is very efficient as recently suggested by the excess of the cosmic near-infrared background radiation that cannot be accounted for by normal galaxy populations. We calculate the luminosity function of X-ray sources in our scenario and find that it is consistent with observed data. Our scenario can explain that ULXs are preferentially found at outskirts of large gas concentrations in star forming regions. A few important physical effects are pointed out and discussed, including gas dynamical friction, radiative efficiency of accretion flow, and radiative feedback to ambient medium. ULXs could last for $\sim 10^{5-6}$ yr to emit a total energy of $\sim 10^{53}$ erg, which is sufficient to power the ionized expanding nebulae found by optical observations.

Keywords. accretion, accretion disks, early universe, X-rays: stars.

1. Introduction

Ultra-Luminous X-ray sources (ULXs, Makishima *et al.* 2000 and references therein) are bright X-ray sources having luminosities greater than $\sim 3 \times 10^{39}$ erg/s found in off-nuclear regions of nearby galaxies. The luminosity exceeds the Eddington limit of a $\sim 20 M_{\odot}$ black hole (BH) that is the maximum mass expected from normal stellar evolutionary paths (Fryer & Kalogera 2001), and their origin is now a matter of hot debate. The high luminosity may also be explained by intermediate mass black holes (IMBHs) of $\gtrsim 100 M_{\odot}$, without violating the Eddington limit. Recently evidence for IMBHs has been accumulating for many ULXs, and it appears that at least a part of ULXs, especially the most luminous ones, are IMBHs.

However, the formation of IMBHs to become ULXs is a challenging problem. It is theoretically expected that IMBHs form as remnants of massive population III (Pop III) stars (e.g., Schneider *et al.* 2002), and they may become ULXs if they accrete sufficient gas in nearby galaxies. However, it is uncertain whether the number of Pop III IMBHs is sufficient to explain the observed number of ULXs by this scenario.

The efficiency of Pop III star formation is highly uncertain, but there are some observational hints. Independent groups (Cambrésy *et al.* 2001; Matsumoto *et al.* 2004) reported detections of the cosmic near-infrared background radiation (CNIB), which cannot be explained by normal galaxy populations (Totani *et al.* 2001). It has been shown that efficient formation of Pop III stars before $z \sim 8$ can explain this unaccounted excess of

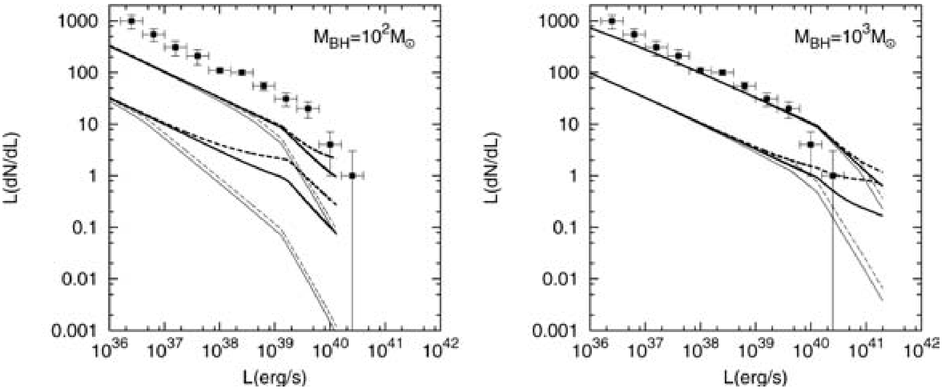

Figure 1. *Left*: The X-ray luminosity function of $M_{\rm BH}$ =100 $M_\odot$ IMBHs normalized to $\text{SFR}_{>5} = 50M_\odot$ yr^{-1}. For each line marking, there are two model curves: the upper one for $\eta = 1$ and the lower one for $\eta = 0.1$. The sound speed is set as $c_s = 0.3$ and 10 km/s for each thick and thin curve, respectively. The dynamical friction parameter is set to be $\xi = 1$ and 10 for each solid and dashed curve, respectively. The data points show the observed universal X-ray luminosity function from Grimm *et al.* (2003). *Right*: Same as the left panel, but for $M_{\rm BH} = 10^3 M_\odot$.

CNIB (Santos, Bromm, & Kamionkowski 2002; Salvaterra & Ferrara 2003); the excess peak at $\sim$1.5μm corresponds to the redshifted Lyman α line emission.

The required amount of Pop III stars to explain the CNIB is somewhat extreme, but not entirely impossible; about $\sim$10% of the cosmic baryons must be converted into Pop III stars. Most of Pop III stars could be massive enough to collapse into IMBHs without any metal ejection, meeting the metallicity constraints from quasar absorption line systems. The consequence of this scenario is that there should be IMBHs in halos of nearby galaxies, whose mass fraction in the baryonic matter is $f_{\rm III} \equiv \Omega_{\rm IMBH}/\Omega_B \sim 0.1$, where $\Omega_B \sim 0.05$ is the cosmic baryon density in the standard definition.

In this paper we show that, if this is the case, such IMBHs passing through dense molecular clouds of star forming regions should have a siginificant contribution to the observed ULX population, especially to the highest luminosity ones.

2. Predicted ULX Luminosity Function

In Fig. 1, we show our prediction of the ULX luminosity function. Both the absolute number and the shape of luminosity function are in agreement with the data. For the details, see the publised paper of Mii & Totani (2005).

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https://doi.org/10.1017/S1743921306008520 Published online by Cambridge University Press